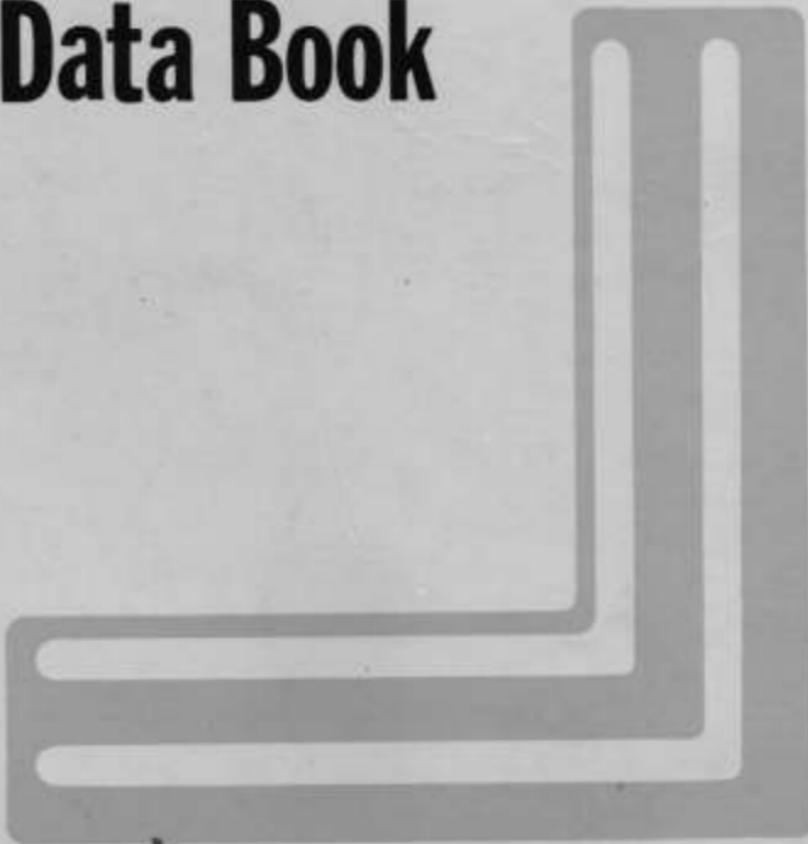


# An Engineering Data Book



Edited by  
A J Munday and R A Farrar

#### REASON FOR PUBLICATION

This book has been produced to provide a pocketable source of data for students pursuing most Engineering Degree Courses, and for use in examinations. \* It was not designed for use in Electrical Degree Courses.

It differs from other data books in two respects; it has a comprehensive key-word index and a symbols index in order that users may find data efficiently.

A Professional Engineer should not rely on the memory of facts for use in a design situation, until their frequent use has committed them permanently and accurately to the memory. Until that happy time is reached a data book makes life easier, and makes the permanent retention of accurate facts more likely.

The editors hope that no errors exist but cannot guarantee the accuracy of the data. If you find any errors the editors would appreciate your comments for inclusion in further editions.

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DJC, JRC, RJF, PWF, SPH, RHM, PJL, SJM, JAO, HJS,  
KVHS, MTT, PLT, DRW, JBW, PW.
- (v) Other engineering data sources too numerous to mention individually for commonly used values and equations.

\* Where permitted by the examining body.

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*Edited by*

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and  
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## 1. UNITS AND ABBREVIATIONS

### 1.1 Decimal prefixes

symbol	prefix	factor by which unit is multiplied
T	tera	$10^{12}$
G	giga	$10^9$
M	mega	$10^6$
k	kilo	$10^3$
h	hecto	$10^2$
da	deca	10
d	deci	$10^{-1}$
c	centi	$10^{-2}$
m	milli	$10^{-3}$
u	micro	$10^{-6}$
n	nano	$10^{-9}$
p	pico	$10^{-12}$

### 1.2 SI units

#### (1) Basic units

unit symbol	unit	quantity
m	metre	length
kg	kilogramme	mass
s	second	time
A	ampere	electric current
K	kelvin	thermodynamic temperature
cd	candela	luminous intensity

#### (ii) Supplementary and derived units

quantity	unit	symbol	equivalent
plane angle	radian	rad	-
force	newton	N	$kg \cdot m/s^2$
work, energy heat	joule	J	N m
power	watt	W	J/s
frequency	hertz	Hz	s <sup>-1</sup>
viscosity:			
kinematic		$m^2/s$	$10^6 cSt$ (centi-stoke)
dynamic		$Ns/m^2 = Pa \cdot s$	$10^3 cP$ (centi-poise)
pressure		$Pa = N/m^2$	Called pascal, Pa
stress		$Pa$ or $N/m^2$	
<u>electrical units</u>			
potential	volt	V	W/A
resistance	ohm	$\Omega$	V/A
charge	coulomb	C	A s
capacitance	farad	F	A s/V
electric field strength	-	V/m	
electric flux density	-	C/m <sup>2</sup>	
<u>magnetic units</u>			
magnetic flux	weber	Wb	V s = Nm/A
inductance	henry	H	V s/A = Nm/A <sup>2</sup>
magnetic field strength	-	A/m	
magnetic flux density	tesla	T	Wb/m <sup>2</sup> = N/(Am)

### 1.3 Conversion factors for other units into SI units

#### Length, area, volume

1 in	= 25.4 mm exactly	$1 \text{ \AA} = 10^{-10} \text{ m}$
1 ft	= 0.3048 m	$1 \text{ thou} = 1 \text{ mil} = 0.001 \text{ in} = 25.4 \mu\text{m}$
1 yd	= 0.914 m	1 micron = 1 μm
1 mile	= 5280 ft = 1.609 km	
1 acre	= 0.4047 ha (Hectare) = 4047 m <sup>2</sup>	
1 in <sup>3</sup>	= 16.39 cm <sup>3</sup>	
1 ft <sup>3</sup>	= 0.02832 m <sup>3</sup>	
1 gal	= 0.1605 ft <sup>3</sup> = 4546 cm <sup>3</sup> = 4.546 l (Litre)	
1 USgal	= 0.1337 ft <sup>3</sup> = 3785 cm <sup>3</sup>	

#### Velocity

1 mile/h	= 1.467 ft/s = 1.609 km/h = 0.447 m/s
1 knot	= 1.689 ft/s = 1.853 km/h = 0.514 m/s

#### Mass

1 lb	= 0.4536 kg
1 slug	= 32.17 lb = 14.59 kg
1 ton	= 2240 lb = 1016 kg
1 tonne	= 1 Mg = 1 metric ton

#### Flowrate

1 ft <sup>3</sup> /s (1 cusec)	= 0.02832 m <sup>3</sup> /s
1 gal/min	= 7.577 10 <sup>-5</sup> m <sup>3</sup> /s = 0.07577 dm <sup>3</sup> /s

#### Density

1 lb/in <sup>3</sup>	= 27.68 g/cm <sup>3</sup>
1 lb/ft <sup>3</sup>	= 16.02 kg/m <sup>3</sup>
1 slug/ft <sup>3</sup>	= 515.4 kg/m <sup>3</sup>

#### Thermal conductivity

1 Btu/ft h deg R	= 1.731 J/m s 0°C = 1.731 W/(mK)
1 cal/cm s deg K	= 418.7 J/m s 0°C = 418.7 W/(mK)

#### Force

1 pdl	= 0.1383 N
1 lbf	= 32.17 pdl = 4.448 N
1 tonf	= 9964 N
1 kgf	= 2.205 lbf = 9.807 N
1 dyne	= 10 <sup>-5</sup> N

#### Torque

1 lbf ft	= 1.356 Nm
1 tonf ft	= 3037 Nm

#### Power

1 hp	= 550 ft lbf/s = 0.7457 kW
1 ft lbf/s	= 1.356 W

1 metric horsepower (ch, PS)	= 0.7355 kW
------------------------------	-------------

#### Energy, work, heat

1 ft lbf	= 1.356 J
1 kW h	= 3.6 MJ
1 Btu	= 778.2 ft lbf = 252 cal = 1055 J
1 cal	= 4.187 J
1 hp h	= 2.685 MJ

#### Pressure, stress

1 lbf/in <sup>2</sup>	= 0.07031 kgf/cm <sup>2</sup> = 6895 N/m <sup>2</sup>
1 tonf/in <sup>2</sup>	= 157.5 kgf/cm <sup>2</sup> = 15.44 MN/m <sup>2</sup>
1 kgf/cm <sup>2</sup>	= 0.09807 MN/m <sup>2</sup> = 0.9807 bar
1 kgf/mm <sup>2</sup>	= 9.807 MN/m <sup>2</sup> = 0.9807 hbar
1 lbf/ft <sup>2</sup>	= 47.88 N/m <sup>2</sup>
1 ft H <sub>2</sub> O	= 62.43 lbf/ft <sup>2</sup> = 2989 N/m <sup>2</sup>
1 in Hg	= 70.73 lbf/ft <sup>2</sup> = 3386 N/m <sup>2</sup>
1 mm Hg	= 1 torr = 133.3 N/m <sup>2</sup>
1 bar	= 14.50 lbf/in <sup>2</sup> = 10 <sup>5</sup> N/m <sup>2</sup>
1 Int atm	= 14.70 lbf/in <sup>2</sup> = 10.34 m water = 1.013 x 10 <sup>5</sup> N/m <sup>2</sup>
	= 1.013 bar = 760 mm Hg = 101.3 kPa

Dynamic viscosity

1 poise (g/cm s)	= 0.1 kg/m s = 0.1 N s/m <sup>2</sup> = 0.1 Pa s
1 kgf s/m <sup>2</sup>	= 0.9807 N s/m <sup>2</sup>
1 lb/ft s	= 0.4132 mN s/m <sup>2</sup>
1 slug/ft s	= 1 lbf s/ft <sup>2</sup> = 47.88 N s/m <sup>2</sup>
1 lbf s/in <sup>2</sup>	= 5895 N s/m <sup>2</sup>

Kinematic viscosity

1 ft <sup>2</sup> /s	= 0.09290 m <sup>2</sup> /s
1 in <sup>2</sup> /s	= 645.2 mm <sup>2</sup> /s
1 cst	= 1 mm <sup>2</sup> /s

Electrical units

The conversion factors which follow are from the C.G.S. system to the S.I. system. (Note: in the C.G.S. system 1 e.m.u. =  $3 \times 10^{10}$  e.s.u. of charge).

capacitance	1 e.s.u. = $\frac{1}{3} \times 10^{-11}$ F
charge	1 e.m.u. = 10 C
current	1 e.m.u. = 10 A
electric field strength	1 e.s.u. = $3 \times 10^4$ V/m
electric flux density	1 e.s.u. = $\frac{1}{12\pi} \times 10^{-5}$ C/m <sup>2</sup>
electric polarisation	1 e.s.u. = $\frac{1}{3} \times 10^{-5}$ C/m <sup>2</sup>
inductance	1 e.m.u. = $10^{-9}$ H
intensity of magnetisation	1 e.m.u. = $10^3$ A/m
magnetic field strength	1 e.m.u. = $\frac{1}{4\pi} \times 10^3$ A/m
magnetic flux	1 e.m.u. = $10^{-8}$ Wb
magnetic flux density	1 e.m.u. = $10^{-4}$ Wb/m <sup>2</sup>
magnetic moment	1 e.m.u. = $10^{-3}$ A m <sup>2</sup>
magnetomotive force	1 e.m.u. = $\frac{10}{4\pi}$ A
mass susceptibility	1 e.m.u/g = $4\pi \times 10^{-3}$ kg <sup>-1</sup>
potential	1 e.m.u. = $10^{-8}$ V
resistance	1 e.m.u. = $10^{-9}$ Ω

2. PHYSICAL CONSTANTS

Avogadro's number	N	= $6.023 \times 10^{26}$ / (kg mol)
Bohr magneton	$\bar{B}$	= $9.27 \times 10^{-24}$ A m <sup>2</sup>
Boltzmann's constant	k	= $1.380 \times 10^{-23}$ J/K
Stefan-Boltzmann constant	$\sigma$	= $5.67 \times 10^{-8}$ W/(m <sup>2</sup> K <sup>4</sup> )
characteristic impedance of $Z_0$ free space		= $(\nu_0/\epsilon_0)^{\frac{1}{2}}$ = 120Ω
electron volt	eV	= $1.602 \times 10^{-19}$ J
electron charge	e	= $1.602 \times 10^{-19}$ C
electronic rest mass	$m_e$	= $9.109 \times 10^{-31}$ kg
electronic charge to mass ratio	e/m <sub>e</sub>	= $1.759 \times 10^{11}$ C/kg
Faraday constant	F	= $9.65 \times 10^7$ C/(kg mol)
permeability of free space	$\mu_0$	= $4\pi \times 10^{-7}$ H/m
permittivity of free space	$\epsilon_0$	= $8.85 \times 10^{-12}$ F/m
Planck's constant	h	= $6.626 \times 10^{-34}$ J s
proton mass	$m_p$	= $1.672 \times 10^{-27}$ kg
proton to electron mass ratio	$m_p/m_e$	= 1836.1
standard gravitational acceleration	g	= $9.80665$ m/s <sup>2</sup> = $9.80665$ N/kg
universal constant of gravitation	G	= $6.67 \times 10^{-11}$ N m <sup>2</sup> /kg <sup>2</sup>
universal gas constant	R <sub>0</sub>	= 8.314 kJ/(kg mol K)
velocity of light in vacuo	c	= $2.9979 \times 10^8$ m/s
volume of 1 kg mol of ideal gas at 1 atm, 0°C		= 22.41 m <sup>3</sup>

Temperature

$$^{\circ}\text{C} = \frac{5}{9} ({}^{\circ}\text{F} - 32)$$

$$^{\circ}\text{K} = \frac{5}{9} ({}^{\circ}\text{F} + 459.67) = \frac{5}{9} {}^{\circ}\text{R} = {}^{\circ}\text{C} + 273.15$$

### 3. SUMMARY OF "BASIC"

This language contains the facilities provided in most versions of extended BASIC. Some instructions may vary somewhat from one system to another; however, equivalents should be available. This applies particularly to String Functions, Commands and Control Codes, and to items marked with a  $\dagger$ . We suggest that you modify the SYSTEM DEPENDENT INSTRUCTIONS MARKED BY  $\dagger$  to conform to your own system and add other instructions in the spaces provided.

#### Arithmetic Variable Names

numeric variables: e.g. A,X;B4,Z1

arithmetic array variables: e.g. S(4),A(I+1),N2(I,J),  
C(I,B(1))

#### String Variable Names

character string variables: e.g. B\$

character string array variables: e.g. Z\$(4),N\$(A,B)

N.B. \$ may be £ on some terminals. Use the key 'shift 4'.

#### Arithmetic Operators

$+$  exponentiation e.g. 2^3 gives 8

$-$  unary minus

$*$  / multiplication, division

$+$  - addition, subtraction

Operations inside any given pair of brackets are performed before those outside. Subject to this, BASIC performs operations in the order of the operators above. The only  $(+)$  exception is  $A+B$ , interpreted as  $A(-B)$ . Operators of equal priority are applied from left to right.

e.g.  $2*(1+3/2*(1+1))$  gives 16

#### Relational Operators (operate upon arithmetic and string values)

$=$   $>$

$<$   $>=$

$<=$  (less than equal to)  $>=$  (not equal to)

#### Logical Operators

AND

XOR exclusive

OR inclusive

#### Matrix Operators

- \* - addition or subtraction of matrices of equal dimensions
- \* - multiplication of conformable matrices
- \* - multiplication of a matrix by a scalar  
e.g. MAT A = (X)\*A

#### Arithmetic Functions (x represents any expression)

PI	has the constant value 3.1415927
SIN(x),COS(x),TAN(x)	sine, cosine, tangent (x in radians)
ATN(x)	arctan (radians)
LOG(x),LOG10(x)	natural log, common log
EXP(x)	exponentiation $e^x$ where $e = 2.71828$
SQR(x)	square root
SGN(x)	sign of x (+ve gives 1, 0 gives 0, -ve gives -1)
ABS(x)	absolute value of x $\{ x \}$
INT(x)	largest integer $\leq x$
RND or RND(x)	returns a random number between 0 and 1. x, if present, is ignored.

#### String Functions

LEN(A\$)	returns the number of characters in the string A\$, including trailing blanks
SUB\$(A\$,N1,N2)	creates a sub string from the string A\$ starting with the N1th character and N2 characters long
SUB\$(A\$,N)	creates a sub string from the string A\$, starting with the Nth character to the last character in A\$
*CHR\$(x)	returns a one character string having the ASCII value x
*ASCII(A\$)	returns the ASCII value of the first character in A\$
NUM\$(N)	creates the string of characters that would be printed by PRINT N:
NUM\$(N,field)	creates the string of characters that would be printed by PRINT USING "field",N:
VAL(A\$)	computes the value that would be generated by the INPUT of the characters of A\$ to an arithmetic variable

\*The ASCII value is based on seven bit characters. Treatment of the parity bit is system dependent.

Error functions (only valid in an error handling routine entered by DNERROR)

ERR contains the error number of the most recent error  
ERL contains the line number of the most recent error

Matrix functions

MAT Y = TRN(X) Y becomes the transpose of X  
MAT Y = INV(X) Y becomes the inverse of X  
DET contains the determinant of X after the evaluation of INV(X)

User defined functions - see DEF statement

Statements

Note - a program line may contain several statements separated by the colon (:) character

Type Example

CLOSE CLOSE 2

DATA DATA 4.3,85,"MONDAY"

DEF DEF FNA(X) = X+X  
DEF FNA(A,B) = SQR(A+B)  
+ DEF FNF(M)  
IF M = 1 THEN FNF = -1 ELSE FNF = M\*FNF(M-1)  
FNEND

DIM DIM A(10),B\$(5,10)

END END must be the last statement of a program

FOR FOR X = 1 TO 10  
FOR N = A TO A+R  
FOR I = 2 TO 40 STEP 2

GOSUB GOSUB 200

GOTO GOTO 151

IF IF B = A THEN Z1  
IF A > Z1 THEN PRINT "BIGGER"  
IF R < N+1 THEN R = N ELSE R = N+2  
IF A > B OR B < C THEN STOP  
IF FNA(R) = B GOTO 200

INPUT INPUT A  
INPUT "TYPE YOUR NAME",A\$  
INPUT #4,N,M

LET LET A = 20  
LET A,B,C = 0  
A\$ = "TEXT" (LET is optional)

MAT

MAT C = CON  
all elements of C = 1  
MAT B = IDN(10,10)  
identity matrix  
MAT A = ZER  
all elements of A = 0  
MAT B = ZER(5,10)  
redimensions and zeros B

MATINPUT

MATINPUT A,B,C(4)  
MATINPUT # 3,A,C

MATPRINT

MATPRINT B  
MATPRINT B(10,5);  
MATPRINT # 2,A

MATREAD

MATREAD A,B(4,4)

NEXT

NEXT I

ON ERROR GOTO

ON ERROR GOTO 140

ON GOSUB

ON X GOSUB 200,250,300  
ON FNA(A) + FNB(A) GOSUB 10,15,30,5

ON GOTO

ON A + 1 GOTO 14,25,50

OPEN

+

PRINT

PRINT A,B  
PRINT "RESULT": X  
PRINT # 4, 1\*A, "EXPERIMENT": N

+ PRINT USING

PRINT USING "# # #", A,B  
PRINT # 3, USING B\$,C,Z\$  
PRINT USING T000,X

RANDOM

RANDOM

READ

READ A,B\$,F1,C

REM

REMARK THIS IS A COMMENT

!

An exclamation mark at the beginning of a line is equivalent to REM  
An exclamation mark after any statement causes the rest of the line to be treated as comment  
X = 0: ZERO CONTROL

RESTORE

RESTORE

RESUME

RESUME  
RESUME 240

RETURN

RETURN

STOP

STOP

TRACE

TRACE

+ \$

PRINTUSING image, e.g. 1000\$ X = # # #

**\*Commands**

RUN	runs the current program
LOAD	loads a program from paper tape (or other medium)
CLEAR }	remove any existing program
NEW }	
LIST	LIST prints the current program LIST n prints line n LIST n-m prints lines n to m
DELETE	DELETE 40-45 deletes specified lines from the current program
SAVE	saves a program on paper tape (or other medium)
REP	edits program line. Any non-numerical character can be used as separator e.g. REP10/x1/A REP30/,B/
RESEQUENCE	renumbers part or all of a program (including GOTO etc references) e.g. RESEQUENCE whole program, steps of 10 RESEQUENCE 900,1000 after old line 900, which becomes 1000, steps of 10 RESEQUENCE,,5 whole program, steps of 5

**\*Special control codes**

ESC }	breaks into the program and stops it, typing BASIC READY
CR }	
RETURN }	terminate a line of input
\ or \$	(on the same key as L, not A) Abandon the current line of input
+ or RUBOUT	delete the previous character or space (may be used repeatedly)

**4. ANALYSES****4.1 Vector algebra**

$$\hat{a} = a/|a|$$

$$a = a_1 \hat{a}_1 + a_2 \hat{a}_2 + a_3 \hat{a}_3 = (a_1, a_2, a_3)$$

$$a = |a| = \sqrt{a_1^2 + a_2^2 + a_3^2}$$

$$a + b = (a_1+b_1, a_2+b_2, a_3+b_3)$$

Scalar (dot) product:

$$a \cdot b = a_1 b_1 + a_2 b_2 + a_3 b_3 = ab \cos \theta$$

Vector (cross) product:

$$a \times b = \begin{vmatrix} \hat{a}_1 & \hat{a}_2 & \hat{a}_3 \\ a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \end{vmatrix} = ab \sin \theta \hat{n} \quad \text{where } \hat{n} \perp a, \hat{n} \perp b$$

Triple scalar product:

$$[a \ b \ c] = a \cdot b \times c = a \times b \cdot c = \begin{vmatrix} a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \\ c_1 & c_2 & c_3 \end{vmatrix}$$

Triple vector product:

$$\begin{aligned} a \times (b \times c) &= (a \cdot c)b - (a \cdot b)c \\ (a \times b) \times c &= (a \cdot c)b - (b \cdot c)a \end{aligned}$$

Differentiation of vectors:

$$\frac{d}{dt}(a + b) = \frac{da}{dt} + \frac{db}{dt} \quad \frac{d}{dt}(f a) = \frac{df}{dt} a + f \frac{da}{dt}$$

$$\frac{d}{dt}(a \cdot b) = a \cdot \frac{db}{dt} + \frac{da}{dt} \cdot b \quad \frac{d}{dt}(a \times b) = a \times \frac{db}{dt} + \frac{da}{dt} \times b$$

$$\frac{d}{dt}(a \cdot b \times c) = \frac{da}{dt} \cdot b \times c + a \cdot \frac{db}{dt} \times c + a \cdot b \times \frac{dc}{dt}$$

Gradient:

$$\text{grad } V = \nabla V = \frac{\partial V}{\partial x} \mathbf{i} + \frac{\partial V}{\partial y} \mathbf{j} + \frac{\partial V}{\partial z} \mathbf{k} \quad (\text{Cartesian})$$

$$= \frac{u_r}{r} \frac{\partial V}{\partial r} + u_\theta \frac{1}{r} \frac{\partial V}{\partial \theta} + u_z \frac{\partial V}{\partial z} \quad (\text{Cylindrical})$$

$$\text{where } u_r = \mathbf{i} \cos\theta + \mathbf{j} \sin\theta$$

$$u_\theta = -\mathbf{i} \sin\theta + \mathbf{j} \cos\theta$$

$$u_z = \mathbf{k}$$



$$= \frac{u_r}{r} \frac{\partial V}{\partial r} + \frac{u_\theta}{r} \frac{\partial V}{\partial \theta} + \frac{u_z}{r \sin\theta} \frac{\partial V}{\partial \phi} \quad (\text{Spherical})$$

$$\text{where } u_r = \mathbf{i} \cos\theta \sin\phi + \mathbf{j} \sin\theta \sin\phi + \mathbf{k} \cos\phi$$

$$u_\theta = \mathbf{i} \cos\theta \cos\phi + \mathbf{j} \sin\theta \cos\phi - \mathbf{k} \sin\phi$$

$$u_\phi = -\mathbf{i} \sin\theta + \mathbf{j} \cos\theta$$

Divergence:

$$\text{div } \mathbf{F} = \nabla \cdot \mathbf{F} = \frac{\partial F_x}{\partial x} + \frac{\partial F_y}{\partial y} + \frac{\partial F_z}{\partial z} \quad (\text{Cartesian})$$

$$= \frac{1}{r} \frac{\partial}{\partial r} (r F_r) + \frac{1}{r} \frac{\partial F_\theta}{\partial \theta} + \frac{\partial F_z}{\partial z} \quad (\text{Cylindrical})$$

$$= \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 F_r) + \frac{1}{r \sin\theta} \frac{\partial}{\partial \theta} (F_\theta \sin\theta) + \frac{1}{r \sin\theta} \frac{\partial F_\phi}{\partial \phi} \quad (\text{Spherical})$$

Curl:

$$\text{curl } \mathbf{F} = \nabla \times \mathbf{F} = \frac{1}{r} \left[ \frac{\partial F_z}{\partial y} - \frac{\partial F_y}{\partial z} \right] \mathbf{i} + \frac{1}{r} \left[ \frac{\partial F_x}{\partial z} - \frac{\partial F_z}{\partial x} \right] \mathbf{j} + \frac{1}{r} \left[ \frac{\partial F_y}{\partial x} - \frac{\partial F_x}{\partial y} \right] \mathbf{k} \quad (\text{Cartesian})$$

$$= \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ F_x & F_y & F_z \end{vmatrix}$$

$$= \frac{1}{r} \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ \frac{\partial}{\partial r} & \frac{\partial}{\partial \theta} & \frac{\partial}{\partial z} \\ F_r & r F_\theta & F_z \end{vmatrix} \quad (\text{Cylindrical})$$

$$= \frac{1}{r^2 \sin\theta} \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ \frac{\partial}{\partial r} & \frac{\partial}{\partial \theta} & \frac{\partial}{\partial \phi} \\ F_r & r F_\theta & r \sin\theta F_\phi \end{vmatrix} \quad (\text{Spherical})$$

Laplace:

$$\nabla \cdot \nabla V = \nabla^2 V = \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} \quad (\text{Cartesian})$$

$$= \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial V}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 V}{\partial \theta^2} + \frac{\partial^2 V}{\partial z^2} \quad (\text{Cylindrical})$$

$$= \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial V}{\partial r} \right) + \frac{1}{r^2 \sin\theta} \frac{\partial}{\partial \theta} \left( \sin\theta \frac{\partial V}{\partial \theta} \right) + \frac{1}{r^2 \sin^2\theta} \frac{\partial^2 V}{\partial \phi^2} \quad (\text{Spherical})$$

Space curves:

$$\mathbf{r} = \frac{d\mathbf{s}}{dt}, \quad s = \text{arc length} \quad \mathbf{u} = \text{unit tangent}$$

$$\mathbf{n} = \frac{d\mathbf{u}}{ds} = \frac{d\mathbf{u}}{dt} \mathbf{u} \quad \mathbf{g} = \text{unit 'inward' normal}$$

$$\frac{d\mathbf{u}}{ds} = \frac{1}{\rho} \mathbf{n}, \quad \rho = \text{radius of curvature}$$

$$\mathbf{b} = \mathbf{u} \times \mathbf{n}, \quad \mathbf{b} = \text{binormal vector}$$

$$\frac{d\mathbf{b}}{ds} = -\frac{1}{\tau} \mathbf{n}, \quad \frac{d\mathbf{u}}{ds} = \frac{1}{\tau} \mathbf{b} - \frac{1}{\rho} \mathbf{u}, \quad \frac{1}{\tau} = \text{torsion}$$

Identities:

$$\nabla \cdot \mathbf{u} = \mathbf{u} \cdot \nabla \mathbf{u} + \mathbf{u} \cdot \nabla \mathbf{u}$$

$$\nabla \times \mathbf{u} = \mathbf{u} \times \nabla \mathbf{u} + \nabla \times \mathbf{u}$$

$$\mathbf{u} \times \mathbf{v} = \mathbf{v} \times \mathbf{u} - \mathbf{u} \times \mathbf{v}$$

#### 4.2 Series

$$(1+x)^a = 1 + ax + \frac{a(a-1)}{2!} x^2 + \frac{a(a-1)(a-2)}{3!} x^3 + \dots$$

for arbitrary  $a$ ,  $|x| < 1$

$$e^x = 1 + x + \frac{x^2}{2!} + \dots + \frac{x^n}{n!} + \dots \text{ for all } x$$

$$\cos x = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \dots + \frac{(-1)^n}{(2n)!} x^{2n} + \dots \text{ for all } x$$

$$\sin x = x - \frac{x^3}{3!} + \frac{x^5}{5!} - \dots + \frac{(-1)^n}{(2n+1)!} x^{2n+1} + \dots \text{ for all } x$$

$$\tan x = x + \frac{x^3}{3} + \frac{2x^5}{15} + \frac{17x^7}{315} + \dots \text{ for } |x| < \pi/2$$

$$\ln(1+x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \dots + \frac{(-1)^n}{(n+1)} x^{n+1} + \dots$$

for  $-1 < x < 1$

Taylor's

$$f(a+h) = f(a) + h f'(a) + \frac{h^2}{2!} f''(a) + \dots$$

$$+ \frac{h^{n-1}}{(n-1)!} f^{(n-1)}(a) + \frac{h^n}{n!} f^{(n)}(c) \text{ where } a < c < a+h$$

Maclaurin's

$$f(x) = f(0) + x f'(0) + \frac{x^2}{2!} f''(0) + \dots$$

$$+ \frac{x^{n-1}}{(n-1)!} f^{(n-1)}(0) + \frac{x^n}{n!} f^{(n)}(ex) \text{ where } 0 < e < 1$$

Stirling's formula for n!

For n large,  $n! \approx \sqrt{2\pi} n^{n+\frac{1}{2}} e^{-n}$   
 or,  $\log_{10} n! \approx 0.39909 + (n+\frac{1}{2}) \log_{10} n + 0.43429n$ .

Fourier series

(i) General formulae  
 If  $f(x)$  is periodic of period  $2L$ ,  $f(x+2L) = f(x)$

$$f(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos \frac{n\pi x}{L} + \sum_{n=1}^{\infty} b_n \sin \frac{n\pi x}{L}$$

where

$$a_n = \frac{1}{L} \int_{-L}^L f(x) \cos \frac{n\pi x}{L} dx \quad n = 0, 1, 2, \dots$$

$$b_n = \frac{1}{L} \int_{-L}^L f(x) \sin \frac{n\pi x}{L} dx \quad n = 1, 2, 3, \dots$$

If  $f(x)$  is an even function of  $x$ , i.e.,  $f(-x) = f(x)$

$$\text{then } a_n = \frac{2}{L} \int_0^L f(x) \cos \frac{n\pi x}{L} dx \quad n = 0, 1, 2, \dots$$

and  $b_n = 0 \quad n = 1, 2, 3, \dots$

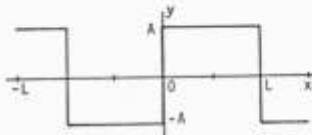
If  $f(x)$  is an odd function of  $x$ , i.e.,  $f(-x) = -f(x)$

$$\text{then } a_n = 0 \quad n = 0, 1, 2, \dots$$

$$\text{and } b_n = \frac{2}{L} \int_0^L f(x) \sin \frac{n\pi x}{L} dx \quad n = 1, 2, 3, \dots$$

(ii) Special waveforms, all of period  $2L$

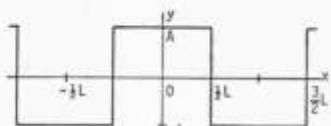
(a) Square wave, sine series



$$f(x) = \frac{4A}{\pi} \left[ \sin \frac{\pi x}{L} + \frac{1}{3} \sin \frac{3\pi x}{L} + \frac{1}{5} \sin \frac{5\pi x}{L} + \dots \right]$$

$$\text{mean square value} = A^2$$

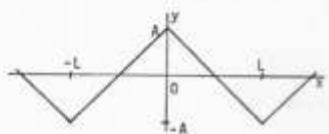
(b) Square wave, cosine series



$$f(x) = \frac{4A}{\pi} \left[ \cos \frac{\pi x}{L} - \frac{1}{3} \cos \frac{3\pi x}{L} + \frac{1}{5} \cos \frac{5\pi x}{L} - \dots \right]$$

$$\text{mean square value} = A^2$$

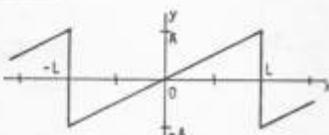
(c) Triangular wave



$$f(x) = \frac{8A}{\pi^2} \left[ \cos \frac{\pi x}{L} + \frac{1}{3^2} \cos \frac{3\pi x}{L} + \frac{1}{5^2} \cos \frac{5\pi x}{L} + \dots \right]$$

$$\text{mean square value} = \frac{A^2}{3}$$

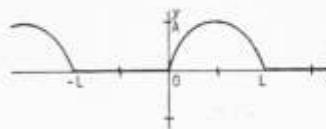
(d) Saw-tooth wave



$$f(x) = \frac{2A}{\pi} \left[ \sin \frac{\pi x}{L} - \frac{1}{3} \sin \frac{3\pi x}{L} + \frac{1}{5} \sin \frac{5\pi x}{L} - \dots \right]$$

$$\text{mean square value} = \frac{A^2}{3}$$

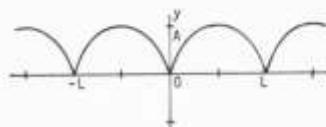
(e) Half-wave rectification



$$f(x) = \frac{A}{2} \sin \frac{\pi x}{L} + \frac{2A}{\pi} \left[ \frac{1}{2} - \frac{1}{3} \cos \frac{2\pi x}{L} + \frac{1}{5} \cos \frac{4\pi x}{L} - \dots \right]$$

$$\text{mean square value} = \frac{A^2}{4} \quad \text{average value} = \frac{A}{2}$$

(f) Full-wave rectification



$$f(x) = \frac{4A}{\pi} \left[ \frac{1}{2} - \frac{1}{3} \cos \frac{2\pi x}{L} - \frac{1}{5} \cos \frac{4\pi x}{L} + \dots \right]$$

$$\text{mean square value} = \frac{A^2}{2} \quad \text{average value} = \frac{2A}{\pi}$$

#### 4.3 Trigonometric, hyperbolic and algebraic relations

$$2 \sin A \cos B = \sin(A+B) + \sin(A-B)$$

$$2 \cos A \cos B = \cos(A-B) + \cos(A+B)$$

$$2 \sin A \sin B = \cos(A-B) - \cos(A+B)$$

$$\sin A + \sin B = 2 \sin \frac{1}{2}(A+B) \cos \frac{1}{2}(A-B)$$

$$\sin A - \sin B = 2 \cos \frac{1}{2}(A+B) \sin \frac{1}{2}(A-B)$$

$$\cos A + \cos B = 2 \cos \frac{1}{2}(A+B) \cos \frac{1}{2}(A-B)$$

$$\cos A - \cos B = -2 \sin \frac{1}{2}(A+B) \sin \frac{1}{2}(A-B)$$

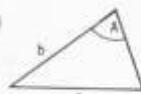
$$\begin{aligned}\sin(A+B) &= \sin A \cos B + \cos A \sin B \\ \cos(A+B) &= \cos A \cos B - \sin A \sin B \\ \tan(A+B) &= \frac{\tan A + \tan B}{1 - \tan A \tan B}\end{aligned}$$

$$\sin^2 A + \cos^2 A = 1$$

$$\sec^2 A = \tan^2 A + 1$$

$$\frac{a}{\sin A} = \frac{b}{\sin B} = \frac{c}{\sin C}$$

$$\begin{aligned}\sin A &= \frac{2}{bc} \sqrt{s(s-a)(s-b)(s-c)} \text{ where } s = \frac{1}{2}(a+b+c) \\ &= \frac{2}{bc} \text{ area} \\ a^2 &= b^2 + c^2 - 2bc \cos A\end{aligned}$$



#### Relation for Spherical Triangles

$$\frac{\sin a}{\sin A} = \frac{\sin b}{\sin B} = \frac{\sin c}{\sin C}$$

$$\begin{aligned}\cos a &= \cos b \cos c + \sin b \sin c \cos A \\ \cos A &= -\cos B \cos C + \sin B \sin C \cos a\end{aligned}$$

$$\frac{\sin \frac{A}{2}}{\sin \frac{a}{2}} = \frac{\sqrt{s(s-b)\sin(s-c)}}{\sin b \sin c} \text{ where } s = \frac{1}{2}(a+b+c)$$

$$\frac{\sin \frac{a}{2}}{\sin \frac{A}{2}} = \frac{\sqrt{\cos b \cos(s-A)}}{\sin b \sin c} \text{ where } s = \frac{1}{2}(A+B+C)$$

#### Napier's Rules for right spherical triangles:

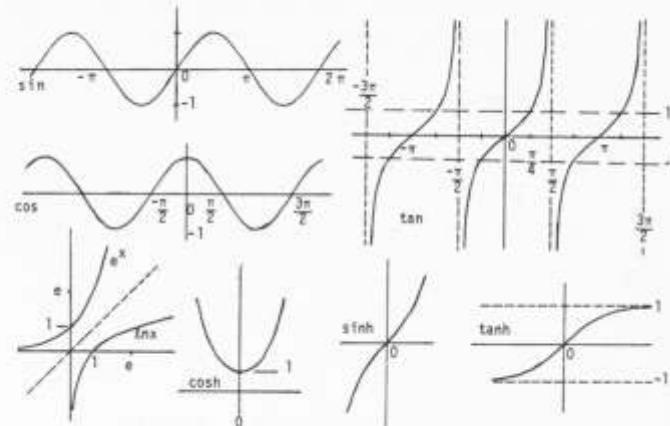
Arrange the five parts about the right angle with 'co' attached to the three parts opposite the right angle. E.g. for the right angle at A we have



N.B. co-a is the complement of a,  
i.e.  $90^\circ - a$

Then: The sine of the middle part is the product of the tangents of adjacent parts and is the product of the cosines of opposite parts.

N.B. A leg and its opposite angle are always in the same quadrant. If the hypotenuse is less than  $90^\circ$  the legs are in the same quadrant, otherwise they are in opposite quadrants.



$$\sin x = \frac{e^{ix} - e^{-ix}}{2i}$$

$$\sinh x = \frac{e^x - e^{-x}}{2}$$

$$\cos x = \frac{e^{ix} + e^{-ix}}{2}$$

$$\cosh x = \frac{e^x + e^{-x}}{2}$$

$$\cos iz = \cosh z$$

$$\cosh iz = \cos z$$

$$\sin iz = i \sinh z$$

$$\sinh iz = i \sin z$$

$$e^z = \cosh z + i \sinh z$$

$$\log_{10}(10^x) = \log_{10}(\text{antilog}_{10}x) = x = 10^{\log_{10}x} = e^{\log_{10}x} = e^{ix}$$

$$a^2 - b^2 = (a+b)(a-b) = a^3 - b^3 = (a-b)(a^2 + ab + b^2)$$

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

#### equations of curves

##### circle

$$x^2 + y^2 = a^2$$

##### ellipse

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$$

##### hyperbolas

$$\frac{x^2}{a^2} - \frac{y^2}{b^2} = 1$$

##### parabola

$$y^2 = 4ax$$

#### 4.4 Complex numbers

$$\begin{aligned} z &= r(\cos\theta + i\sin\theta) = x + iy \\ &= r e^{i(\theta+2n\pi)} \quad (n = 0, \pm 1, \pm 2, \dots) \end{aligned}$$

$$e^{iz} = \cos z + i \sin z \quad [\text{Euler's Formula}]$$

$$x + iy = \sqrt{x^2 + y^2} e^{i \tan^{-1}(y/x)}; \quad z^c = e^{ciz}$$

N.B.  $\tan^{-1}(y/x)$  must be chosen to lie in the appropriate quadrant

#### 4.5 Partial differentiation

(a) If  $F = f(x, y)$ , where  $x = X(t)$ ,  $y = Y(t)$  then

$$F = F(t) \text{ and } \frac{dF}{dt} = \frac{\partial f}{\partial x} \frac{dx}{dt} + \frac{\partial f}{\partial y} \frac{dy}{dt}$$

(b) If  $F = f(x, y)$ , where  $y = Y(x)$ , then  $F = F(x)$  and

$$\frac{dF}{dx} = \frac{\partial f}{\partial x} + \frac{\partial f}{\partial y} \frac{dy}{dx}$$

(c) If  $F = f(x, y)$ , where  $x = X(u, v)$ ,  $y = Y(u, v)$  then

$$F = F(u, v) \text{ and } \frac{\partial F}{\partial u} = \frac{\partial f}{\partial x} \frac{\partial x}{\partial u} + \frac{\partial f}{\partial y} \frac{\partial y}{\partial u},$$

$$\frac{\partial F}{\partial v} = \frac{\partial f}{\partial x} \frac{\partial x}{\partial v} + \frac{\partial f}{\partial y} \frac{\partial y}{\partial v}.$$

#### 4.6 Differential Equations

##### (i) First Order

Type	Characteristic	Method of solution
separable	$y' = P(x)Q(y)$	rearrange: $\int \frac{1}{Q(y)} dy = \int P(x) dx + c$
homogeneous	$y' = f\left(\frac{y}{x}\right)$	by substitution $y = ux$ to make equation separable
exact	$M(x, y)dx + N(x, y)dy$ where $\frac{\partial M}{\partial y} = \frac{\partial N}{\partial x}$	$\frac{\partial G}{\partial x} = M, \quad \frac{\partial G}{\partial y} = N$ Solve for $G$
linear	$y' + P(x)y = Q(x)$	multiply through by $e^{\int P(x)dx}$

#### (ii) Second Order, linear with constant coefficients

$$m\ddot{x} + a\dot{x} + kx = 0$$

$$\ddot{x} + 2\xi\omega_0 \dot{x} + \omega_0^2 x = 0, \quad t = \frac{x}{\omega_0}, \quad \omega_0 = \sqrt{\frac{k}{m}}$$

(a)  $\xi < 1$  (underdamping)

$$x = e^{-\xi\omega_0 t} \cos(\omega t - \theta)$$

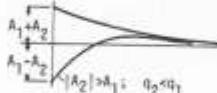
$$u = \omega_0 \sqrt{1 - \xi^2}$$



(b)  $\xi > 1$  (overdamping)

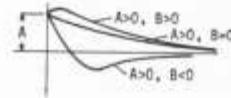
$$x = A_1 e^{-q_1 t} + A_2 e^{-q_2 t}$$

$$\text{where } q_1, q_2 = \omega_0 \{ \xi \pm \sqrt{\xi^2 - 1} \}$$



(c)  $\xi = 1$  (critical damping)

$$x = (A + Bt)e^{-\xi\omega_0 t}$$



#### Forced oscillations

$$\ddot{x} + 2\xi\omega_0 \dot{x} + \omega_0^2 x = a \cos pt, \quad a = \frac{F}{m}, \quad x_1 = \frac{F}{k}$$

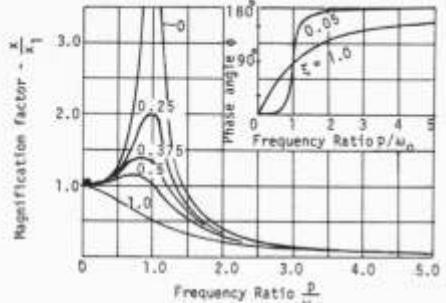
$$x = Aa \cos(pt - \phi)$$

$$T_{\text{ang}} = \frac{\omega_0}{\sqrt{1 - \xi^2}}$$

$$A = \left| \frac{x}{x_1} \right| = \frac{1}{\left[ \left( 1 - \left( \frac{p}{\omega_0} \right)^2 \right)^2 + \left( 2\xi \frac{p}{\omega_0} \right)^2 \right]^{\frac{1}{2}}}$$

$$\text{At resonance } p = \omega_0 \sqrt{1 - 2\xi^2}$$

$$x = \frac{x_1}{2\xi\sqrt{1 - \xi^2}} \quad \text{Tang} = \frac{\sqrt{1 - 2\xi^2}}{2\xi}$$



#### 4.7 Rules of Differentiation and Integration

$$\frac{d}{dx}(uv) = u \frac{dv}{dx} + v \frac{du}{dx}$$

$$\frac{d}{dx}(uvw) = uv \frac{dw}{dx} + uw \frac{dv}{dx} + vw \frac{du}{dx}$$

$$\frac{d}{dx}\left(\frac{u}{v}\right) = \frac{1}{v^2} \left(v \frac{du}{dx} - u \frac{dv}{dx}\right)$$

$$\int uv \, dx = uw - \int u \, dw \, dx, \text{ where } w = \int v \, dx$$

#### 4.8 Standard Differentials and Integrals

$$\frac{d}{dx} x^n = nx^{n-1}$$

$$\int x^n \, dx = \frac{x^{n+1}}{n+1} + C, \quad n \neq -1$$

$$\frac{d}{dx} \ln|x| = \frac{1}{x}$$

$$\int \frac{dx}{x} = \ln|x|$$

$$\frac{d}{dx} e^{ax} = ae^{ax}$$

$$\int e^{ax} \, dx = \frac{e^{ax}}{a} + C, \quad a \neq 0$$

$$\frac{d}{dx} a^x = a^x \ln a$$

$$\int a^x \, dx = \frac{a^x}{\ln a} + C, \quad a > 0, \quad a \neq 1$$

$$\frac{d}{dx} x^x = x^x(1+\ln x)$$

$$\int \ln x \, dx = x(\ln x - 1)$$

$$\frac{d}{dx} \sin x = \cos x$$

$$\int \cos x \, dx = \sin x$$

$$\frac{d}{dx} \cos x = -\sin x$$

$$\int \sin x \, dx = -\cos x$$

$$\frac{d}{dx} \tan x = \sec^2 x$$

$$\int \sec^2 x \, dx = \tan x$$

$$\frac{d}{dx} \cot x = -\operatorname{cosec}^2 x$$

$$\int \operatorname{cosec}^2 x \, dx = -\cot x$$

$$\frac{d}{dx} \sin^{-1} x = \frac{1}{\sqrt{1-x^2}}$$

$$\int \frac{dx}{\sqrt{1-x^2}} = \sin^{-1} x, \quad |x| < 1$$

$$\frac{d}{dx} \tan^{-1} x = \frac{1}{1+x^2}$$

$$\int \frac{dx}{1+x^2} = \tan^{-1} x$$

$$\frac{d}{dx} \cosh x = \sinh x$$

$$\int \sinh x \, dx = \cosh x$$

$$\frac{d}{dx} \sinh x = \cosh x$$

$$\int \cosh x \, dx = \sinh x$$

$$\frac{d}{dx} \tanh x = \operatorname{sech}^2 x$$

$$\int \operatorname{sech}^2 x \, dx = \tanh x$$

$$\frac{d}{dx} \coth x = -\operatorname{cosech}^2 x$$

$$\int \operatorname{cosech}^2 x \, dx = -\coth x$$

$$\frac{d}{dx} \sinh^{-1} x = \frac{1}{\sqrt{1+x^2}}$$

$$\int \frac{dx}{\sqrt{1+x^2}} = \sinh^{-1} x \\ = \ln |x + \sqrt{(1+x^2)}|$$

$$\frac{d}{dx} \cosh^{-1} x = \frac{1}{\sqrt{x^2-1}}$$

$$\int \frac{dx}{\sqrt{x^2-1}} = \cosh^{-1} x \\ = \ln |x + \sqrt{(x^2-1)}|, x \geq 1$$

$$\frac{d}{dx} \tanh^{-1} x = \frac{1}{1-x^2}$$

$$\int \frac{dx}{1-x^2} = \tanh^{-1} x \\ = \frac{1}{2} \ln \left| \frac{1+x}{1-x} \right|, \quad x^2 < 1$$

$$\frac{d}{dx} \coth^{-1} x = \frac{1}{1-x^2}$$

$$\int \frac{dx}{x^2-1} = -\coth^{-1} x \\ = \frac{1}{2} \ln \left| \frac{x-1}{x+1} \right|, \quad x^2 > 1$$

### Some definite integrals (m, n integers)

$$\int_0^{\frac{\pi}{2}} \sin^m x dx = \int_0^{\frac{\pi}{2}} \cos^m x dx = \begin{cases} \frac{n-1}{n} \frac{n-3}{n-2} \cdots \frac{3}{2} \frac{1}{2} \frac{\pi}{2} & n \text{ even} \\ \frac{n-1}{n} \frac{n-3}{n-2} \cdots \frac{4}{3} \frac{2}{3} 1 & n \text{ odd} \end{cases}$$

$$I_{m,n} = \int_0^{\frac{\pi}{2}} \sin^m x \cos^n x dx = \binom{m-1}{m+n} I_{m-2,n} = \binom{n-1}{m+n} I_{m,n-2}, \quad m \neq -n$$

$$\int_0^{\pi} \sin mx \sin nx dx = \int_0^{\pi} \cos mx \cos nx dx = 0 \quad (m \neq n)$$

$$\int_0^{\pi} \sin mx \cos nx dx = 0$$

$$\int_0^{\infty} e^{-ax} \sin bx dx = \frac{b}{a^2 + b^2}, \quad a > 0$$

$$\int_0^{\infty} e^{-ax} \cos bx dx = \frac{a}{a^2 + b^2}, \quad a > 0$$

$$\int_0^{\infty} e^{-x^2} dx = \frac{\sqrt{\pi}}{2}$$

The error function  $\operatorname{erf}z = \frac{2}{\sqrt{\pi}} \int_0^z e^{-u^2} du$  (refer to page 30 for tabulated value)

$$\int_0^{\pi} \frac{\sin \theta \cos \theta}{(1+\cos \theta)^2} d\theta = \frac{-2e^{-\frac{\pi}{2}}}{(1-e^{-\frac{\pi}{2}})^2}$$

$$\int_0^{\pi} \frac{\sin^2 \theta d\theta}{(1+\cos \theta)^2} = \frac{\pi}{2(1-e^{-\frac{\pi}{2}})^2/2}$$

$$\int_0^{2\pi} \frac{d\theta}{(1+\cos \theta)} = \frac{2\pi}{(1-e^{-\frac{\pi}{2}})^{1/2}}$$

### 4.9 Laplace Transforms

#### Definition

$$F(s) = L[f(t)] = \int_0^{\infty} f(t)e^{-st} dt$$

#### Theorems

$$\text{Linearity} \quad L[af(t) + bg(t)] = aF(s) + bG(s)$$

$$\text{Final Value} \quad \lim_{t \rightarrow \infty} f(t) = \lim_{s \rightarrow 0} sF(s)$$

$$\text{Initial Value} \quad \lim_{t \rightarrow 0} f(t) = \lim_{s \rightarrow \infty} sF(s)$$

$$\text{Differentiation} \quad L\left[\frac{df(t)}{dt}\right] = sF(s) - f(0)$$

$$\text{Integration} \quad L\left[\int f(t) dt\right] = \frac{F(s)}{s} + \frac{f(0)}{s}$$

$$\text{First Shifting} \quad L[e^{at} f(t)] = F(s-a)$$

$$\text{Second Shifting} \quad L[f(t-a)] \quad t > a = e^{-as} F(s)$$

$$\text{Convolution} \quad L[f * g] = L\left[\int_0^t f(u)g(t-u) du\right] = F(s)G(s)$$

$$\text{Partial Differentiation} \quad L\left[\frac{\partial f(t, \alpha)}{\partial \alpha}\right] = \frac{\partial}{\partial \alpha} F(s, \alpha)$$

$$\text{Time Multiplication} \quad L[tf(t)] = -\frac{dF(s)}{ds}$$

#### Transform Pairs

##### Function

$$1$$

$$H(t-T) = \begin{cases} 0 & t < T \\ 1 & t \geq T \end{cases}$$

$$t^n$$

$$e^{-at}$$

$$\sin \omega t$$

$$\cos \omega t$$

$$1 - e^{-t/T}$$

$$\frac{u_n}{\sqrt{1-\xi^2}} e^{-\xi u_n t} \sin(u_n \sqrt{1-\xi^2} t)$$

##### Laplace Transform

$$\frac{1}{s}$$

$$\frac{1}{s} e^{-sT}$$

$$\frac{n!}{s^{n+1}}$$

$$\frac{1}{s+a}$$

$$\frac{u}{s^2 + \omega^2}$$

$$\frac{s}{s^2 + \omega^2}$$

$$\frac{1}{s(1+s)}$$

$$\frac{1}{1 + 2\frac{\xi s}{u_n} + \frac{s^2}{u_n^2}}$$

$$1 - \frac{1}{\sqrt{1-\xi^2}} e^{-\xi \omega_n t} \sin \left[ \omega_n \sqrt{1-\xi^2} t + \cos^{-1} \xi \right] = \frac{1}{s \left( 1 + \frac{1}{2} \frac{\xi}{\omega_n} + \frac{\xi^2}{\omega_n^2} \right)}$$

#### 4.10 Numerical analysis

##### (i) Approximate solution of an algebraic equation $f(x) = 0$

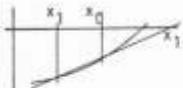
###### (a) Newton's Method

$$x_1 = x_0 - \frac{f(x_0)}{f'(x_0)}$$



###### (b) Secant Method

$$x_1 = \frac{x_0 f(x_{-1}) + x_{-1} f(x_0)}{f(x_0) - f(x_{-1})}$$



##### (ii) Least-squares fitting of a straight line

If  $y_i$  ( $i = 1, 2, \dots, n$ ) are the experimentally observed values of  $y$  at chosen (exact) values of  $x_i$  of the variable  $x$ , the line of 'best fit' passes through the centroid

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad \bar{y} = \frac{1}{n} \sum_{i=1}^n y_i$$

and is given by  $y = mx + c$  where,

$$m = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sum (x_i - \bar{x})^2}, \quad c = \bar{y} - m\bar{x}$$

$$= \frac{\sum x_i y_i - n\bar{x}\bar{y}}{\sum x_i^2 - n\bar{x}^2}$$

##### (iii) Finite-difference formulae

$$\Delta f(x) = f(x+h) - f(x)$$

$$f'(x) = \frac{f(x+h) - f(x-h)}{2h} + O(h^2)$$

$$f''(x) = \frac{f(x+h) - 2f(x) + f(x-h)}{h^2} + O(h^2)$$

$$f'''(x) = \frac{f(x+2h) - 2f(x+h) + 2f(x-h) - f(x-2h)}{2h^3}$$

##### (iv) Lagrange's interpolation formula for unequal intervals.

The polynomial  $P(x)$  of degree 2 passing through the three points  $(x_i, y_i)$ ,  $i = 1, 2, 3$ , is

$$P(x) = \frac{(x-x_2)(x-x_3)}{(x_1-x_2)(x_1-x_3)} y_1 + \frac{(x-x_1)(x-x_3)}{(x_2-x_1)(x_2-x_3)} y_2 + \frac{(x-x_1)(x-x_2)}{(x_3-x_1)(x_3-x_2)} y_3$$

##### (v) Formulas for numerical integration

Equal intervals  $h$

$$x_n = x_0 + nh, \quad y_n = y(x_n)$$

###### (a) Trapezoidal Rule (1-strip):

$$\int_{x_0}^{x_1} y(x) dx = \frac{h}{2} [y_0 + y_1] + \epsilon, \quad \epsilon = -\frac{h^3}{12} y'' \text{ or, } -\frac{h}{12} \Delta^2 y_0$$

###### (b) Simpson's Rule (2-strip):

$$\int_{x_0}^{x_2} y(x) dx = \frac{h}{3} [y_0 + 4y_1 + y_2] + \epsilon, \quad \epsilon = -\frac{h^5}{90} y^{(4)} \text{ or, } -\frac{h}{90} \Delta^4 y_0$$

##### (vi) Runge-Kutta

$$\text{2nd order: } y_{n+1} = y_n + \frac{h}{2} \left[ f(x_n, y_n) + f(x_n + h, y_n + k_1) \right]$$

$$\text{4th order: } y_{n+1} = y_n + \frac{1}{6} (k_1 + 2k_2 + 2k_3 + k_4)$$

$$k_1 = hf(x_n, y_n)$$

$$k_2 = hf \left[ x_n + \frac{h}{2}, y_n + \frac{k_1}{2} \right]$$

$$k_3 = hf \left[ x_n + \frac{h}{2}, y_n + \frac{k_2}{2} \right]$$

$$k_4 = hf(x_n + h, y_n + k_3)$$

## 5. ANALYSIS OF EXPERIMENTAL DATA

### 5.1 Probability distributions for discrete random variables

Notation:  $P(r) = f(r) \Rightarrow$  the probability distribution of random variable  $r$  is  $f(r)$

$$\mu = \text{mean value of } r = \sum_{i=1}^N r_i f(r_i)$$

$$\sigma^2 = \text{variance of } r = \sum_{i=1}^N r_i^2 f(r_i) - \mu^2$$

$$\binom{n}{r} = \text{binomial coefficient} = \frac{n!}{(n-r)!r!} = \binom{n}{n-r}$$

evaluate using Pascal's Triangle

$r = 0$	$1$	$2$	$3$	$4$	$5$	$6$	$7$	$8$	$9$	$10$
$n = 0$	1									
1	1	1								
2	1	2	1							
3	1	3	3	1						
4	1	4	6	4	1					
5	1	5	10	10	5	1				
6	1	6	15	20	15	6	1			
7	1	7	21	35	35	21	7	1		
8	1	8	28	56	70	56	28	8	1	
9	1	9	36	84	126	126	84	36	9	1
10	1	10	45	120	210	252	210	120	45	10

### (a) Binomial:

$n$  = number of trials with constant probability  $p$  of success in each

$r$  = number of successes

$$P(r) = \binom{n}{r} p^r (1-p)^{n-r} \quad r = 0, 1, 2, \dots, n$$

$$\mu = np, \quad \sigma^2 = np(1-p)$$

### (b) Poisson:

$\mu$  = mean rate of occurrence of an event

$r$  = number of events actually occurring in unit time

$$P(r) = e^{-\mu} \mu^r / r! \quad r = 0, 1, \dots$$

$$\sigma^2 = \mu$$

### 5.2 Probability distributions for continuous random variables

#### (a) Exponential:

$$\text{probability density function } f(x) = \lambda e^{-\lambda x},$$

$$x \geq 0, \lambda > 0$$

$$\mu = 1/\lambda$$

$$\sigma^2 = 1/\lambda^2$$

#### (b) Normal: the standardised normal distribution, $N(0,1)$

has probability density function

$$f(z) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}z^2}$$

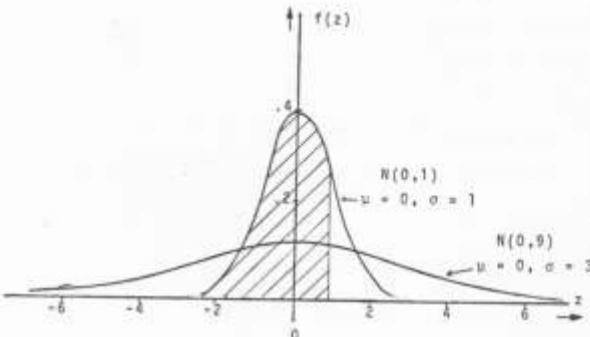
$$\mu = 0$$

$$\sigma = 1$$

$\Phi$  = cumulative distribution function

$\Phi(z) = \text{probability that the random variable is observed to have a value } \leq z \text{ (the shaded area shown)}$

$$\Phi(z) = \int_{-\infty}^z \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}t^2} dt$$



For negative  $z$  use  $\Phi(-z) = 1 - \Phi(z)$

$z$	$\Phi(z)$	$z$	$\Phi(z)$	$z$	$\Phi(z)$
0.0	.5000	1.0	.8413	2.0	.9772
.1	.5398	.1	.8643	.1	.9821
.2	.5793	.2	.8849	.2	.9861
.3	.6179	.3	.9032	.3	.9893
.4	.6554	.4	.9192	.4	.9918
.5	.6915	1.5	.9332	2.5	.9938
.6	.7257	.6	.9452	.6	.9953
.7	.7580	.7	.9554	.7	.9965
.8	.7881	.8	.9641	.8	.9974
.9	.8159	.9	.9713	.9	.9981
				3.0	.9987
				4.0	.99997

Percentage points of the Normal Distribution  $N(0,1)$

$\Phi(z)$	$\% \{1\text{-tail}\}$	$\% \{2\text{-tails}\}$	$z$
.9500	5.0	10	1.6449
.9750	2.5	5	1.9600
.9900	1.0	2	2.3263
.9950	0.5	1	2.5758

The general normal distribution  $N(\mu, \sigma^2)$  has probability density function  $f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/2\sigma^2}$ ,  $-\infty < x < \infty$

where  $\int_{-\infty}^{\infty} f(x)dx = 1$

and cumulative distribution function  $F(x)$

$$F(x) = \int_{-\infty}^{(x-\mu)/\sigma} \frac{1}{\sqrt{2\pi}} e^{-u^2/2} du = \Phi\left(\frac{x-\mu}{\sigma}\right)$$

To use tables of  $\Phi(z)$ , take  $z = \frac{x-\mu}{\sigma}$ .

### 5.3 Experimental Samples

$x_1, x_2, \dots, x_n$  denote a set of  $n$  observations of a random variable having a normal distribution whose population mean  $\mu$  is unknown.

$$\text{Range} = x_{\text{max}} - x_{\text{min}}$$

$$\text{Sample mean } \bar{x} = \frac{1}{n} \sum x_i$$

$$\text{Average deviation} = \frac{1}{n} \sum |x_i - \bar{x}|$$

$$\text{Sample standard deviation} = s.$$

$$\text{Sample variance} = s^2 = \frac{1}{n-1} \sum (x_i - \bar{x})^2$$

$$\text{Distribution of } \bar{x} \text{ is } N(\mu, \sigma^2/n)$$

$$\text{Distribution of } s \text{ is } N(\sigma, \sigma^2/n)$$

$$\text{Distribution of } \frac{\bar{x}-\mu}{(s/\sqrt{n})} \text{ is } N(0,1)$$

$$\text{i.e. standard error of sample means} = \frac{\sigma}{\sqrt{n}}$$

If population variance  $\sigma^2$  is known,

$$95\% \text{ confidence interval for } \mu \text{ is } \bar{x} \pm 1.96 \sigma/\sqrt{n}$$

$$99\% \text{ confidence interval for } \mu \text{ is } \bar{x} \pm 2.58 \sigma/\sqrt{n}$$

If population variance  $\sigma^2$  is unknown:  $\frac{\bar{x}-\mu}{s/\sqrt{n}}$  has the t-distribution

with  $n-1$  degrees of freedom ( $t_{n-1}$ ) and the 95% confidence interval for  $\mu$  is obtained from  $\bar{x} \pm t_{\alpha/2, n-1} s/\sqrt{n}$  and the table.

### 95% points of the t-distribution

$n-1$	$t_{\alpha/2}$	$n-1$	$t_{\alpha/2}$	$n-1$	$t_{\alpha/2}$
1	12.7	6	2.45	12	2.18
2	4.30	7	2.36	15	2.13
3	3.18	8	2.31	20	2.09
4	2.78	9	2.26	30	2.04
5	2.57	10	2.23	60	2.00
				=	1.96

Thus for  $n > 20$ ,  $\bar{x} \pm 1.96 s/\sqrt{n}$  is a good approximation to the population mean with a 95% confidence.

### 3.4 Combination of Errors

If results are Normally Distributed, the Most Probable Error  $s_z$  in the calculated result  $z = f(x, y, \text{etc.})$ , due to the independent standard errors  $s_x, s_y, \text{etc.}$  in  $x, y, \text{etc.}$  is given by,

$$(s_z)^2 = \left[ \frac{\partial z}{\partial x} s_x \right]^2 + \left[ \frac{\partial z}{\partial y} s_y \right]^2 + \dots \text{etc.}$$

If the function  $f$  consists of multiplied and divided terms ONLY (i.e. no addition or subtraction)

$$\left( \frac{s_z}{z} \right)^2 = \left[ n \frac{s_x}{x} \right]^2 + \left[ m \frac{s_y}{y} \right]^2 + \dots \text{etc.}$$

where  $n, m, \text{etc.}$  are the powers of  $x, y, \text{etc.}$  in  $f$ .

#### Notes

- (1) The Maximum Possible Error ( $(\bar{s}_z) = \frac{\partial z}{\partial x} \bar{s}_x + \frac{\partial z}{\partial y} \bar{s}_y, \text{etc.}$ ) is rarely of interest in engineering
- (2) Instrument 'rounding off' error  $\delta s_x$  may be treated as a Normally Distributed error by the equivalence  $s_x \approx \frac{2}{3} \delta s_x$ .

### 6. MECHANICS

#### Moments of inertia and Second moments of area - General theorems

N.6. The symbol  $I$  is used for both second moment of area and moment of inertia.

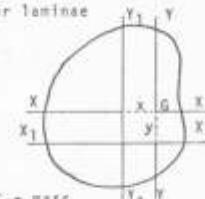
##### (i) Parallel axis theorem: Solids or laminae

Centroid is at  $G$

Centre of mass is at  $G$

$$I_{X_1 X_1} = I_{XX} + Cy^2$$

$$I_{Y_1 Y_1} = I_{YY} + Cx^2$$



where for moment of inertia  $C = \text{mass}$   
and for second moment of area of a lamina  $C = \text{area}$

##### (ii) Perpendicular axis theorem for laminae:

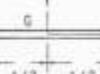
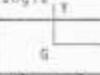
$$\text{Polar second moment } I_0 = I_{XX} + I_{YY} = I_{ZZ}$$

#### Radius of gyration $k$

$$\text{Second moment of area } I = Ak^2$$

$$\text{Moment of inertia } I = mk^2$$

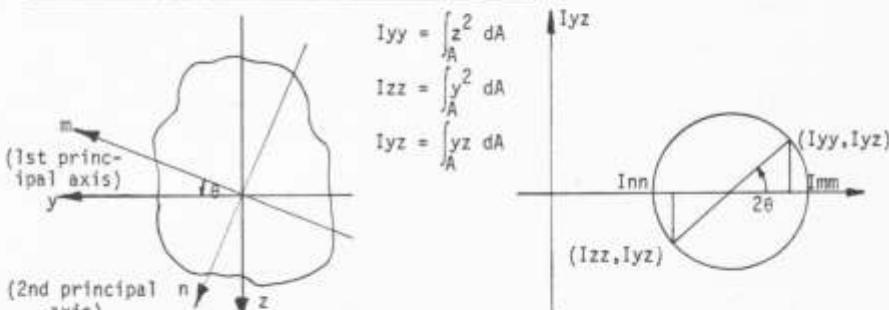
where  $A = \text{area}, m = \text{mass}$ .

(a) UNIFORM ROD	$k_{XX}^2$	$k_{YY}^2$	$A$
	$\frac{l^2}{12}$	$\frac{t^2}{12}$	$lt$
(b) LAMINAE			
Rectangle 	$\frac{1}{12} d^2$	$\frac{1}{12} b^2$	$bd$
Circle 	$\frac{1}{4} a^2$	$\frac{1}{4} a^2$	$\pi a^2$

(b) LAMINAE (cont)	$k_{XX}^2$	$k_{YY}^2$	A
Semi-circle	$a^2 \left  \frac{1}{4} - \left( \frac{4}{3\pi} \right)^2 \right $	$\frac{1}{4} a^2$	$\frac{\pi a^2}{2}$
Triangle	$\frac{1}{18} h^2$ $k_{XY}^2 = \frac{1}{36} h(b_1 - b_2)$	$\frac{1}{18} (b_1^2 + b_1 b_2 + b_2^2)$	$\frac{h}{2}(b_1 + b_2)$
Ellipse	$\frac{b^2}{4}$	$\frac{a^2}{4}$	$\pi a b$
(c) SOLIDS	$k_{XX}^2$	$k_{YY}^2$ and $k_{ZZ}^2$	$V$
Cylinder	$\frac{1}{2} a^2$	$\frac{1}{4} a^2 + \frac{1}{12} z^2$	$\pi a^2 z$
Thin-walled cylinder	$a^2 + \frac{1}{4} t^2$	$\frac{1}{2} a^2 + \frac{1}{8} t^2 + \frac{1}{12} z^2$	$2\pi a t z$
Thick walled cylinder	$\frac{1}{2}(R^2 + r^2)$	$\frac{z^2}{12} + \frac{R^2 + r^2}{4}$	$\pi(R^2 - r^2)z$

(c) SOLIDS (cont)	$k_{XX}^2$ and $k_{ZZ}^2$	$k_{YY}^2$	$V$
Sphere	$\frac{2}{5} a^2$	$\frac{2}{5} a^2$	$\frac{4}{3} \pi a^3$
Cone	$\frac{3(4a^2 + h^2)}{80}$	$\frac{3a^2}{10}$	$\frac{\pi}{3} a^2 h$

#### Mohr's Circle for Second Moment of Area



#### Constant acceleration equations

$$\begin{aligned} v &= u + at \\ v^2 &= u^2 + 2ax \\ x &= ut + \frac{1}{2} at^2 \end{aligned}$$

#### Friction

coefficient of static friction  $\mu = \tan \phi$   
for no slipping  $\frac{F}{N} \leq \mu$

#### Accelerations due to rotation

$$\text{Coriolis} = 2 \omega \times \left( \frac{\partial r}{\partial t} \right)$$

$$\text{Central} = \omega \times (\omega \times r)$$

#### DRY SLIDING FRICTION COEFFICIENTS

Clutches	0.3-0.4
Brakes (lining)	0.35-0.5
" (pads)	~0.3
Nylon/Steel	0.3-0.5
Filled PTFE/Steel	0.05-0.3
Perspex/Steel	~0.5
Rubber/Steel	0.6-0.9
Rubber/Asphalt	0.5-0.8
Lignum vitae/Steel	~0.1

## 7. PROPERTIES AND MECHANICS OF SOLIDS

### 7.1 Bonding

(a) London-Morse Equation  $V_{\text{total}} = \frac{-4\pi e^2}{r^n} + \frac{B}{r^m} + C$

(b) Ionic Bond Equation  $V_0 = \frac{-2\pi r_0^2 e^2}{4\pi \epsilon_0} \left(1 - \frac{1}{n}\right) + kE$

(c) Theoretical Density  $\rho = \frac{nA}{VN}$

### 7.2 Atomic sizes in substitutional alloys

Element	Seitz radius $r_s$ (Å) (at 200°C)	Effective valency in solution
Al	1.58	3
Au	1.59	1
Cu	1.41	1
Fe(α)	1.41	?
Mg	1.05	2
Ni	1.38	1
P	1.58	3
Pb	1.95	4
Si	1.67	4
Sn	1.86	4
Zn	1.54	2

### 7.3 Phase Transformations

Length and volume changes may be related by:-

$$(1 + \Delta V/V) = (1 + \Delta L/L)^3$$

### 7.4 Crystallography

#### (a) In the Miller system:

Specific Plane  $\{h, k, l\}$

Family of Planes  $\{h, k, l\}$

Specific Direction  $[h, k, l]$

Family of Directions  $\langle h, k, l \rangle$

#### (b) Inter-planar spacings for Cubics

$$d_{\{h, k, l\}} = \frac{a}{\sqrt{h^2 + k^2 + l^2}} = \frac{a}{\sqrt{N}}$$

### (c) Quadratic Forms of Miller Indices (N values)

#### Cubic Structure

#### N values

Simple	1, 2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 16, 17, 18, 19, 20, ...
Face Centred	3, 4, 8, 11, 12, 16, 19, 20, 24, 27, 32, ...
Body Centred	2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 30, ...
Diamond	3, 8, 11, 16, 19, 24, 27, 32, ...

### 7.5 Defects and Diffusion Data

(a) Number of Defects  $n = \alpha N^{1/3}$

(b) Diffusivity  $D = D_0 e^{-\frac{E}{RT}}$

Note: these equations may be expressed in terms of Peierls rather than  $k$ , the value of  $D$  must be quoted in the appropriate units.

#### (c) Macroscopic Diffusion

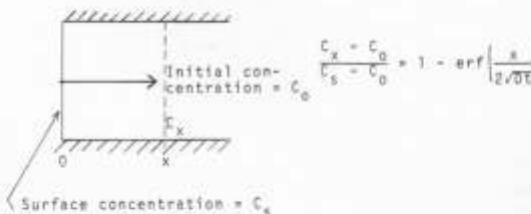
(i)  $D$  constant with composition,  $\frac{dc}{dx}$  constant with time  

$$J = -D \frac{dc}{dx}$$
 (This is a special case of (ii))

(ii)  $D$  constant with composition,  $\frac{dc}{dx}$  varies with time  

$$\frac{dc}{dt} = D \frac{d^2 c}{dx^2}$$

Solution for a constant surface potential and impermeable sides



7.6 Selected Values of Error Function  $\sqrt{\frac{2}{\pi}} \int_0^z e^{-u^2} du$

$z$	$erf z$						
0.00	0.0000	0.68	0.6638	1.36	0.9456	2.00	0.9953
0.02	0.0226	0.70	0.6778	1.38	0.9490	2.05	0.9963
0.04	0.0451	0.72	0.6914	1.40	0.9523	2.10	0.9970
0.06	0.0676	0.74	0.7047	1.42	0.9554	2.15	0.9976
0.08	0.0901	0.76	0.7175	1.44	0.9583	2.20	0.9981
0.10	0.1125	0.78	0.7300	1.46	0.9611	2.25	0.9983
0.12	0.1348	0.80	0.7421	1.48	0.9637	2.30	0.9989
0.14	0.1570	0.82	0.7538	1.50	0.9661	2.35	0.9991
0.16	0.1790	0.84	0.7651	1.52	0.9684	2.40	0.9993
0.18	0.2009	0.86	0.7761	1.54	0.9706	2.45	0.9995
0.20	0.2227	0.88	0.7867	1.56	0.9726	2.50	0.9996
0.22	0.2443	0.90	0.7969	1.58	0.9746	2.55	0.9997
0.24	0.2657	0.92	0.8068	1.60	0.9764	2.60	0.9998
0.26	0.2869	0.94	0.8163	1.62	0.9780	2.65	0.9998
0.28	0.3079	0.96	0.8254	1.64	0.9796	2.70	0.9999
0.30	0.3286	0.98	0.8342	1.66	0.9811	2.75	0.9999
0.32	0.3491	1.00	0.8427	1.68	0.9825	2.80	0.9999
0.34	0.3694	1.02	0.8508	1.70	0.9838	2.85	0.9999
0.36	0.3893	1.04	0.8587	1.72	0.9850	2.90	1.0000
0.38	0.4090	1.06	0.8661	1.74	0.9861	2.95	1.0000
0.40	0.4284	1.08	0.8733	1.76	0.9872	3.00	1.0000
0.42	0.4475	1.10	0.8802	1.78	0.9882	4.00	1.0000
0.44	0.4662	1.12	0.8868	1.80	0.9891		
0.46	0.4847	1.14	0.8931	1.82	0.9899		
0.48	0.5028	1.16	0.8991	1.84	0.9907		
0.50	0.5205	1.18	0.9048	1.86	0.9915		
0.52	0.5379	1.20	0.9103	1.88	0.9922		
0.54	0.5549	1.22	0.9155	1.90	0.9928		
0.56	0.5716	1.24	0.9205	1.92	0.9934		
0.58	0.5879	1.26	0.9252	1.94	0.9939		
0.60	0.6039	1.28	0.9297	1.96	0.9944		
0.62	0.6194	1.30	0.9340	1.98	0.9949		
0.64	0.6346	1.32	0.9381				
0.66	0.6494	1.34	0.9419				

7.7 Fracture

i) Fatigue

Manson-Coffin Law  $\sqrt{N_p} \cdot \sigma_p = c$  ( $c$  = constant)

Miner's Rule  $\frac{\sum n_i}{NT} = 1$

Rayleigh Distribution  $P(\sigma) = \sigma^{-2} \exp \left\{ -\frac{1}{2} \left( \frac{\sigma}{\sigma_r} \right)^2 \right\}$

Fraction of peak exceeding stress ( $\sigma$ ) expressed in terms of  $E$   $E(\sigma) = \exp \left\{ -\frac{1}{2} \left( \frac{\sigma}{\sigma_r} \right)^2 \right\}$

ii) Fracture Toughness

Stress Intensity  $K = Q \sigma \sqrt{a}$

Paris Equation  $\frac{da}{dt} = A(\Delta K)^n = A_1 a^{m/2}$  ( $A$ ,  $A_1$ ,  $n$  and  $m$  are constants)

7.8 Some typical values of physical properties

All values are given, unless otherwise stated, for a temperature of 20°C.

	Carbon Steel	Alumi-nium Alloys	Brass 65/35	Copper	Concrete	Stain-less Steels	Wood
$\rho$ ( $\text{kg/m}^3$ )	7850	2720	8450	8960	2400	8000	400-800
$E$ ( $\text{GN/m}^2$ )	207	68.9	105	104	13.8	213	8-13
$G$ ( $\text{GN/m}^2$ )	79.6	26.5	38.0	46		82	
$K$ ( $\text{GN/m}^{3/2}$ )	172	57.5	115	130		178	
$\nu$	0.3	0.3	0.35	0.35	0.1	0.3	
$\alpha$ ( $\mu\text{m}/(\text{mK})$ )	11	23	19	11.2		18	~0.1%
$\sigma_y$ ( $\text{MN/m}^2$ )	230-460	30-280	62-430	47-320		200-585	
$\sigma_f$ ( $\text{MN/m}^2$ )	400-770	90-300	330-530	200-350	27-55	500-800	50-100

$K$  for water is  $2.3 \text{ GN/m}^{3/2}$

The lower values of  $\sigma_y$  and  $\sigma_f$  for carbon and stainless steels refer to materials such as plates and tubes while the higher figures refer to heat-treated material such as used for bolts. The range of values for aluminium, copper and brass is due to the change in material property achieved by heat-treatment and/or mechanical work.

7.6 Selected Values of Error Function  $\frac{2}{\sqrt{\pi}} \int_0^z e^{-u^2} du$

z	erf z						
0.00	0.0000	0.68	0.6638	1.36	0.9456	2.00	0.9953
0.02	0.0226	0.70	0.6778	1.38	0.9490	2.05	0.9963
0.04	0.0451	0.72	0.6914	1.40	0.9523	2.10	0.9970
0.06	0.0676	0.74	0.7047	1.42	0.9554	2.15	0.9976
0.08	0.0901	0.76	0.7175	1.44	0.9583	2.20	0.9981
0.10	0.1125	0.78	0.7300	1.46	0.9611	2.25	0.9983
0.12	0.1348	0.80	0.7421	1.48	0.9637	2.30	0.9989
0.14	0.1570	0.82	0.7538	1.50	0.9661	2.35	0.9991
0.16	0.1790	0.84	0.7651	1.52	0.9684	2.40	0.9993
0.18	0.2009	0.86	0.7761	1.54	0.9706	2.45	0.9995
0.20	0.2227	0.88	0.7867	1.56	0.9726	2.50	0.9996
0.22	0.2443	0.90	0.7969	1.58	0.9746	2.55	0.9997
0.24	0.2657	0.92	0.8068	1.60	0.9764	2.60	0.9998
0.26	0.2869	0.94	0.8163	1.62	0.9780	2.65	0.9998
0.28	0.3079	0.96	0.8254	1.64	0.9796	2.70	0.9999
0.30	0.3286	0.98	0.8342	1.66	0.9811	2.75	0.9999
0.32	0.3491	1.00	0.8427	1.68	0.9825	2.80	0.9999
0.34	0.3694	1.02	0.8508	1.70	0.9838	2.85	0.9999
0.36	0.3893	1.04	0.8587	1.72	0.9850	2.90	1.0000
0.38	0.4090	1.06	0.8661	1.74	0.9861	2.95	1.0000
0.40	0.4284	1.08	0.8733	1.76	0.9872	3.00	1.0000
0.42	0.4475	1.10	0.8802	1.78	0.9882	4.00	1.0000
0.44	0.4662	1.12	0.8868	1.80	0.9891		
0.46	0.4847	1.14	0.8931	1.82	0.9899		
0.48	0.5028	1.16	0.8991	1.84	0.9907		
0.50	0.5205	1.18	0.9048	1.86	0.9915		
0.52	0.5379	1.20	0.9103	1.88	0.9922		
0.54	0.5549	1.22	0.9155	1.90	0.9928		
0.56	0.5716	1.24	0.9205	1.92	0.9934		
0.58	0.5879	1.26	0.9252	1.94	0.9939		
0.60	0.6039	1.28	0.9297	1.96	0.9944		
0.62	0.6194	1.30	0.9340	1.98	0.9949		
0.64	0.6346	1.32	0.9381				
0.66	0.6494	1.34	0.9419				

7.7 Fracture

i) Fatigue

Manson-Coffin Law  $\sqrt{P_D} \cdot \sigma_P = c$  ( $c$  = constant)

Miner's Rule  $\left[ \frac{n_1}{N_1} \right] + \left[ \frac{n_2}{N_2} \right] + \dots = 1$

Rayleigh Distribution  $P(\sigma) = \sigma^{-2} \exp \left\{ -\frac{1}{2} \left( \frac{\sigma}{\sigma_r} \right)^2 \right\}$

Fraction of peak exceeding stress ( $\sigma$ ) expressed in terms of  $E$   $F(\sigma) = \exp \left\{ -\frac{1}{2} \left( \frac{\sigma}{\sigma_r} \right)^2 \right\}$

ii) Fracture Toughness

Stress Intensity  $K = Q \sigma \sqrt{a}$

Paris Equation  $\frac{da}{dt} = A(\Delta K)^n = K_1 a^{m/2}$  ( $A$ ,  $K_1$ ,  $n$  and  $m$  are constants)

7.8 Some typical values of physical properties

All values are given, unless otherwise stated, for a temperature of 20°C.

	Carbon Steel	Alumi-nium Alloys	Brass 65/35	Copper	Concrete	Stain-less Steels	Wood
$\rho$ (kg/m <sup>3</sup> )	7850	2720	8450	8960	2400	8000	400-800
$E$ (GN/m <sup>2</sup> )	207	68.9	105	104	13.8	213	8-13
$G$ (GN/m <sup>2</sup> )	79.6	26.5	38.0	46		82	
$K$ (GN/m <sup>3/2</sup> )	172	57.5	115	130		178	
$\nu$	0.3	0.3	0.35	0.35	0.1	0.3	
$\alpha$ (μm/(mK))	11	23	19	11.2		18	~0.15
$\sigma_y$ (MN/m <sup>2</sup> )	230-460	30-280	62-430	47-320		200-585	
$\sigma_t$ (MN/m <sup>2</sup> )	400-770	90-300	330-530	200-350	27-55	500-800	50-100

K for water is 2.3 GN/m<sup>3/2</sup>

The lower values of  $\sigma_y$  and  $\sigma_t$  for carbon and stainless steels refer to materials such as plates and tubes while the higher figures refer to heat-treated material such as used for bolts. The range of values for aluminium, copper and brass is due to the change in material property achieved by heat-treatment and/or mechanical work.

Metals

Property	Copper	Iron
Crystal structure	f.c.c.	b.c.c.
Bonding	metallic	metallic
Lattice constant (Å)	3.61	2.86
Atomic volume (m <sup>3</sup> /kg mol)	$7.09 \times 10^{-3}$	$7.10 \times 10^{-3}$
ρ (kg/m <sup>3</sup> )	$8.96 \times 10^3$	$7.87 \times 10^3$
Resistivity (Ω m)	$1.72 \times 10^{-8}$	$10 \times 10^{-8}$
Cohesive energy (J/kg mol)	$3.38 \times 10^8$	$4.05 \times 10^8$
Melting point (°C)	1083	1530
α(μm/mK)	16.7	12.1
Fermi energy (eV)	7.04	11.2
Work Function (eV)	4.07 - 4.18	3.91 - 4.77
Temperature coefficient of resistance (K <sup>-1</sup> )	+0.0043	+0.0065
Effective radius (Å) of		
(a) neutral atom	1.27	1.26
(b) singly charged ion	0.96	-
(c) doubly charged ion	0.70	0.75

Semiconductors

Property	Germanium	Silicon
Crystal structure	diamond	diamond
Bonding	covalent	covalent
Lattice constant (Å)	5.6575	5.4307
Atomic volume (m <sup>3</sup> /kg mol)	$13.5 \times 10^{-3}$	$12.0 \times 10^{-3}$
Density (kg/m <sup>3</sup> )	$5.32 \times 10^3$	$2.33 \times 10^3$
Cohesive energy (J/kg mol)	$3.72 \times 10^8$	$4.39 \times 10^8$
Melting point (°C)	958.5	1412
Mobility (m <sup>2</sup> /V s)	{electrons 0.38 holes 0.18}	{electrons 0.19 holes 0.05}
Energy gap (eV) (room temperature)	0.67	1.107
Density of states effective mass	{electrons 0.35 m <sub>e</sub> holes 0.56 m <sub>e</sub> }	{electrons 0.58 m <sub>e</sub> holes 1.06 m <sub>e</sub> }
α(μm/mK)	5.75	7.6

Polymers

PROPERTY	Polyethylene (H <sub>2</sub> O)	Polyvinyl Chloride	Polyisobutylene
Polymer Structure	$\left[ -\text{CH}_2-\text{CH}_2-\right]_n$	$\left[ -\text{CH}_2-\text{CH}(\text{Cl})-\right]_n$	$\left[ -\text{CH}_2-\text{CH}(\text{CH}_3)_2-\right]_n$
Structural State	Crystalline	Amorphous/ Slightly Crystalline	Amorphous/ Crystalline
ρ (kg/m <sup>3</sup> )	$0.96 \times 10^3$	$1.7 \times 10^3$	$1.05 \times 10^3$
Resistivity (Ω m)	$10^6 - 10^{10}$	$10^5$	$10^{10}$
α(μm/mK)	120	190	63
ε (GN/m <sup>2</sup> )	70-280	2500-3500	3500-4200
σ <sub>f</sub> (MN/m <sup>2</sup> )	7-14	28-40	35-50
T <sub>g</sub> (K)	153	353	373
PROPERTY	Polymethyl-methacrylate	Polytetrafluoroethylene	Polyisoprene (Natural) Rubber
Polymer Structure	$\left[ -\text{CH}_2-\text{CH}(\text{CH}_3)-\text{C}(\text{H}_3)=\text{CH}_2-\right]_n$	$\left[ -\text{CF}_2-\text{CF}_2-\right]_n$	$\left[ -\text{CH}_2-\text{C}(\text{H}_3)=\text{CH}-\text{CH}_2-\right]_n$
Structural State	Amorphous	Crystalline	Elastomer
ρ (kg/m <sup>3</sup> )	$1.2 \times 10^3$	$2.2 \times 10^3$	$1.5 \times 10^3$
Resistivity (Ω m)	$10^8$	$10^8$	$10^5 - 10^7$
α(μm/mK)	90	100	-
ε (GN/m <sup>2</sup> )	2500-4000	400-650	7-70
σ <sub>f</sub> (MN/m <sup>2</sup> )	50-70	14-30	2-10
T <sub>g</sub> (K)	380	399	203
PROPERTY	Nylon 6:6	Phenol-Formaldehyde Resin (Bakelite)	
Polymer Structure	$\left[ -\text{NH}-\text{CH}_2-\text{NH}-\text{C}(=\text{O})-\text{CH}_2-\text{NH}-\text{C}(=\text{O})-\text{CH}_2-\right]_n$	$\left[ \text{CH}_2-\text{CH}(\text{OH})-\text{CH}_2-\text{CH}(\text{OH})-\text{CH}_2-\right]_n$	
Structure State	Crystalline	Amorphous	
ρ (kg/m <sup>3</sup> )	$1.15 \times 10^3$	$1.3 \times 10^3$	
Resistivity (Ω m)	$10^6$	$10^4$	
α(μm/mK)	100	72	
ε (GN/m <sup>2</sup> )	2000-3000	7000	
σ <sub>f</sub> (MN/m <sup>2</sup> )	50-70	50	
T <sub>g</sub> (K)	323	-	

- The atomic number indicates the number of protons in the nucleus of an atom. In the neutral atom these protons are electrically balanced by an equal number of electrons outside the nucleus. Only neutral atoms are considered in the Periodic Classification.
- Electrons travel far from the nucleus but if those regions where they spend most of their time are considered, a well-defined pattern of layers or 'Principal Shells' appears. Each shell is known by a Principal Quantum Number 1, 2, 3, ... 7 or sometimes by the letters K, L, M, ... etc.
- In each shell the electrons move around the nucleus in complicated, three-dimensional patterns called Orbitals. The laws of Quantum Mechanics permit only certain types of orbital. An electron following one of these paths possesses an amount of energy (Energy Level) characteristic of that orbital.
- Four types of orbital are encountered; they are identified by the letters  $s$ ,  $p$ ,  $d$  and  $f$ .  $s$  is the simplest whilst  $p$ ,  $d$  and  $f$  are progressively more complex.
- The number of orbitals per shell increases with shell number. (See the lower diagram overleaf.) The first contains only an  $s$  orbital, the second an  $s$  and three  $p$ 's, the third adds five  $d$  orbitals and the fourth seven  $f$ 's. These groups of like orbitals in any Principal Shell are called  $s$ ,  $p$ ,  $d$  or  $f$  sub-shells. Each sub-shell, depending on its principal quantum number and type, has a characteristic energy the order of which is generally proportional to the distance of the sub-shell from the nucleus.
- Each orbital accepts either one or two electrons and the maximum number of electrons per sub-shell is shown on the diagram.
- Electrons take positions in orbitals where the energy level is lowest. Up to element 18 (Argon) sub-shells and shells are built in an orderly sequence to maximum capacity. But in the next group the order changes because it happened that the energy level of the  $4s$  state is a little lower than that of the  $3d$  state.
- The first transition series begins with Scandium (element 21) where the energy levels of the  $4s$  and  $3d$  orbitals are so nearly equal that there is a tendency for electrons to move from one orbital to another, causing variable valency. The same happens in the fifth period with  $5s$  and  $4d$  orbitals and in the sixth period with the  $6s$  and  $5d$  orbitals.
- In the Lanthanide and Actinide series of elements, the  $4f$  and  $5f$  orbitals are occupied only after the  $3p$ ,  $d$  and  $s$  orbitals outside them have filled or begun to fill. The effect upon the chemistry of the elements is very small because the  $f$  orbitals are deep in the core of the atom. For this reason there is little difference between one element and its immediate neighbours.
- In any element, the so called Valency Electrons are those moving in orbitals of the highest energy levels. In this Chart of the Periodic Classification, the number and position of the valency electrons is indicated in the boxes underneath the various columns e.g. Rhodium-element 45--has nine valency electrons, 8 in the  $4s$  sub-shell and 1 in the  $5s$ .

#### NOTE

1. The following atomic weights are based on the exact number 12 for the carbon isotope  $^{12}\text{C}$ , as agreed between the International Union of Pure and Applied Physics and of Pure and Applied Chemistry, 1961.

2. The values given normally indicate the mean atomic weight of the mixture of isotopes found in nature. Particular attention is drawn to the value for hydrogen, boron, carbon, oxygen, silicon and sulphur, where the deviation shown is due to variation in relative concentration of isotopes.

Symbol	Name	Atomic Number	Atomic Weight	Symbol	Name	Atomic Number	Atomic Weight
A or Ar	Argon	18	39.948	Mg	Magnesium	12	24.312
Ac	Actinium	89	—	Mn	Manganese	25	54.9380
Ag	Silver	47	107.870	Mo	Molybdenum	42	95.94
Al	Aluminium	13	26.9815	N	Nitrogen	7	14.0667
Am	Ameritium	95	—	Na	Sodium	11	22.9888
As	Arsenic	33	74.9216	Nb	Hafnium	41	92.906
At	Atmosine	85	—	Nd	Neodymium	60	144.24
Au	Gold	79	196.967	Ne	Neon	10	20.183
B	Boron	5	10.811	Ni	Nickel	28	58.71
		± 0.003		No	Nobelium	102	—
Ba	Barium	56	137.34	Np	Neptunium	93	—
Be	Beryllium	4	9.0122	O	Oxygen	8	15.9994
Bi	Bismuth	83	208.980				± 0.0001
Bk	Berkelium	97	—	Os	Osmium	76	190.2
Br	Bromine	35	79.909	P	Phosphorus	15	30.9738
C	Carbon	6	12.01115	Pa	Protactinium	91	—
		± 0.00005	Pb	Lead	82	207.19	
Ca	Calcium	20	40.08	Pd	Palladium	46	106.4
Cd	Cadmium	48	112.40	Pm	Promethium	61	—
Ce	Cerium	58	140.12	Po	Polonium	84	—
Cl	Californium	98	—	Pr	Praseodymium	59	140.907
Cl	Chlorine	17	35.453	Pt	Platinum	78	195.09
Cm	Curium	56	—	Pu	Plutonium	94	—
Co	Cobalt	27	58.9332	Ra	Radium	88	—
Cr	Chromium	24	51.996	Rb	Rubidium	37	85.47
Cs	Cesium	55	132.905	Re	Rhenium	75	186.2
Cs	Copper	29	63.54	Rh	Rhodium	45	102.905
Dy	Dysprosium	66	162.50	Rn	Radon	86	—
Er	Erbium	68	167.26	Ru	Ruthenium	44	101.07
Es	Einsteinium	99	—	S	Sulphur	16	32.064
Eu	Europium	63	151.96				± 0.003
F	Fluorine	9	18.9984	Sb	Antimony	51	121.75
Fe	Iron	26	55.847	Sc	Scandium	21	44.956
Fm	Fermium	100	—	Se	Selenium	34	78.96
Fr	Francium	87	—	Si	Silicon	14	28.086
Ga	Gallium	31	69.72				± 0.001
Gd	Gadolinium	64	157.25	Sm	Samarium	62	150.35
Ge	Germanium	32	72.59	Ta	Tantalum	73	180.948
H	Hydrogen	1	1.0079	Tb	Terbium	65	158.924
		± 0.00001	Tc	Technetium	43	—	
He	Helium	2	4.0026	Tc	Tellurium	52	127.60
Hf	Hafnium	72	178.49	Th	Thorium	90	232.038
Hg	Mercury	80	200.59	Ti	Titanium	23	47.90
Ho	Holmium	67	164.930	Tl	Thallium	81	204.37
I	Iodine	53	126.9044	Tm	Thulium	69	168.934
In	Indium	49	114.82	U	Uranium	92	238.03
Ir	Iridium	77	192.2	V	Vanadium	23	50.942
K	Potassium	19	39.102	W	Tungsten	74	183.85
Kr	Krypton	36	83.80	Xe	Xenon	54	131.30
La	Lanthanum	57	138.91	Y	Yttrium	39	88.905
Li	Lithium	3	6.939	Yb	Ytterbium	70	173.04
Lu	Lutetium	71	174.97	Zn	Zinc	30	65.37
Md	Mendelevium	101	—	Zr	Zirconium	40	91.22

## 8. THERMODYNAMICS AND FLUID MECHANICS

### 8.1 Thermodynamic Relationships

1st Law	$dQ = dW + dU$
Enthalpy	$H = U + pV$ or $h = u + pV$
For reversible process	$dS = \left(\frac{dQ}{T}\right)_{rev}$ or $dQ = TdS$
= = =	$dW = pdV$
Helmholtz function	$F = U - TS$ or $f = u - Ts$
Gibbs function	$G = H - TS$ or $g = h - Ts$
Gibbs free energy	
From 1st Law for a homogeneous fluid	$Tds = du + pdv + dh - vdp$
Specific heat at constant volume	$c_v = \left(\frac{\partial u}{\partial T}\right)_V$
Specific heat at constant pressure	$c_p = \left(\frac{\partial u}{\partial T}\right)_p$
Specific heat ratio	$\gamma = c_p/c_v$
Reversible engine (Carnot) efficiency	$\eta = 1 - (T_{sink}/T_{source})$
Engine indicated Power	$P_i = p_m V_s N_c$
Steady flow energy equation	$(0-W)/m = h_2 - h_1 + \frac{1}{2}(c_2^2 - c_1^2) + g(z_2 - z_1)$
Continuity equation	$\dot{m} = \rho A c$
General relationships for a perfect gas:	
$pv = RT$	$pV = RT$
$pV_0 = R_0 T$	$MR = R_0$
$\Delta U = mc_v(T_2 - T_1)$	$\Delta H = mc_p(T_2 - T_1)$
$\Delta S = mc_v \ln\left(\frac{T_2}{T_1}\right) + mc_p \ln\left(\frac{V_2}{V_1}\right)$	
$c_p - c_v = R$	$\frac{\gamma-1}{\gamma} = \frac{R}{c_p}$
Van der Waals' equation $(p + \frac{a}{V^2})(V - b) = RT$	
$S = k \ln P$	$k = R_0/N$
Availability, (closed system): $(A_1 - A_0) = (U_1 + p_0 V_1 - T_0 S_1) - (U_0 + p_0 V_0 - T_0 S_0)$	
	$= (flow process) : (B_1 - B_0) = (H_1 - T_0 S_1) - (H_0 - T_0 S_0)$
Maximum work of a Reaction $W_{max} = G_{react} - G_{prod} = R_0 T \ln(K_p, p, T)$	

For reversible polytropic ( $pV^n = \text{constant}$ ) closed system:  
 $W = (p_1V_1 - p_2V_2)/(n-1)$

For perfect gas also:

$$W = mR(T_1 - T_2)/(n-1) \quad \frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} = \left(\frac{V_1}{V_2}\right)^{n-1}$$

$$0 = \frac{T_2 - T_1}{T_1 - T_2} \cdot n \cdot R$$

For adiabatic reversible (isentropic reversible):

$$n = \gamma$$

For isothermal reversible:

$$W = 0 = pV \ln\left(\frac{V_1}{V_2}\right) \quad (n = 1)$$

#### Maxwell relations

$$\left(\frac{\partial T}{\partial V}\right)_S = -\left(\frac{\partial p}{\partial S}\right)_V \quad \left(\frac{\partial T}{\partial p}\right)_S = \left(\frac{\partial V}{\partial S}\right)_p$$

$$\left(\frac{\partial p}{\partial T}\right)_V = \left(\frac{\partial S}{\partial V}\right)_T \quad \left(\frac{\partial V}{\partial T}\right)_p = -\left(\frac{\partial S}{\partial p}\right)_T$$

#### Heat transfer

Conduction (one dimensional)  $\dot{Q}/A = -k dT/dx$   
 $= k(T_1 - T_2)/x_{1,2}$

" (radial flow)  $\dot{Q}/E = 2\pi k \Delta T / \ln(r_2/r_1)$

Forced convection in a tube  $Nu = 0.023 Re^{0.8} Pr^{0.4}$   
 (characteristic length = hydraulic mean diameter) (see 8.5)

Log. mean temperature difference  $\frac{\Delta T_{in} - \Delta T_{out}}{\ln(\Delta T_{in}/\Delta T_{out})} = \Delta T_m$

Stefan-Boltzmann Law of radiation  $q_b = \sigma T^4$

Radiation exchange:

Grey body to black or large enclosure  $\dot{Q}/A = \sigma \epsilon_1 [T_1^4 - T_2^4]$

Large parallel grey surfaces  $\dot{Q}/A = \frac{\sigma}{1/\epsilon_1 + 1/\epsilon_2} [T_1^4 - T_2^4]$

Heat transfer coefficient  $h = \dot{Q}/A\Delta T$   
 emissivity  $\epsilon = q/q_b$

#### Fluid Mechanics

##### Statics

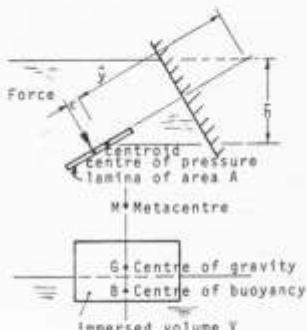
$$\frac{\partial p}{\partial z} = -\rho g$$

$$\text{Force} = \rho g A h$$

$$c = \frac{(Ak^2)_{\text{centroid}}}{Ag}$$

$$\overline{GM}_{\text{roll}} = \frac{Ak^2}{V} - \overline{GM}$$

( $Ak^2$  is 2nd moment of area about rolling axis)



##### Dynamics

For simple Newtonian flow  $\tau = u \frac{dy}{dx}$

Euler's equation  $\frac{1}{\rho} \frac{dp}{dx} + c \frac{dc}{dx} + g \frac{dz}{dx} = 0$

Bernoulli's equation  $\frac{p}{\rho g} + \frac{c^2}{2g} + z = \text{constant}$

For constant area flow with friction (Fanno)

$$\frac{dp}{\rho} + c \frac{dc}{dx} + 2 \frac{fc^2}{D} dx = 0$$

Acceleration along a stream-line  $a_s = V_s \frac{\partial V_s}{\partial x} + \frac{\partial V_s}{\partial t}$

Acceleration normal to a streamline  $a_n = \frac{V_s^2}{r} + \frac{\partial V_n}{\partial t}$

Reynolds' Equation for bearings:

$$\frac{3}{8\pi} \left( \frac{\rho h^3}{12\pi} \frac{dp}{dx} \right) + \frac{3}{8y} \left( \frac{\rho h^3}{12\pi} \frac{dp}{dy} \right) = \frac{1}{2} \frac{3}{\pi x} (\rho h) + \frac{3}{8\pi} (\rho h) + \rho w$$

$$\frac{1}{r} \frac{3}{8\pi} \left( \frac{\rho h^3}{12\pi} \frac{dp}{dr} \right) + \frac{1}{r^2} \frac{3}{8\pi} \left( \frac{\rho h^3}{12\pi} \frac{dp}{dr} \right) = \frac{1}{2} \frac{3}{\pi r} (\rho h) + \frac{3}{8\pi} (\rho h) + \rho w$$

##### Hydraulic machines

Head coefficient  $\psi = Y/\omega^2 D^2$

Flow  $\phi = Q/\omega D^3$

Dimensionless specific speed  $n_s = \left| \frac{\omega^{1/2} / Y^{1/4} \cdot \psi^{1/2} \cdot \phi^{1/3}}{\rho^{1/2} \cdot g^{1/2}} \right| n_{MAX}$

Dimensionless diameter  $\Delta = DY^{\frac{1}{2}}/Q^{\frac{1}{3}}$   
 Dimensionless suction specific speed  $N_{ss} = \omega Q^{\frac{1}{2}}/(\text{NPSE})^{\frac{1}{2}}$   
 Cavitation number  $\sigma$  or  $k = (P_w - P_v)/(\frac{1}{2}\rho V_w^2)$ , suffix w = reference condition.  
 Cavitation number (Thoma)  $c_{Th} = (P_1 - P_v)/(P_2 - P_1)$   
 suffix 1, abs pressure at top side of machine; suffix 2, abs pressure at bp side of machine; suffix v, vapour pressure

### Open Channel Hydraulics

Chézy equation  $V = CVRS$

Manning equation:  $V = \frac{1}{n} R^{\frac{3}{5}} S^{\frac{1}{2}}$

Steady gradually varied flow equation:  $\frac{dy}{dx} = \frac{S_0 - S_f}{1 - \frac{y}{2g}}$  (rectangular channel)

Unsteady gradually varied flow equation:  $\frac{dy}{dx} + \frac{y}{g} \frac{\partial V}{\partial x} + \frac{1}{g} \frac{\partial V}{\partial t} = S_0 - S_f$  no local inflow or

Continuity equation:  $A \frac{\partial V}{\partial x} + V \frac{\partial A}{\partial x} + T \frac{\partial d}{\partial t} = 0$  outflow

Conjugate depths in hydraulic jump:  $\frac{d_2}{d_1} = \frac{1}{2} \left[ \sqrt{1 + 8F_1^2} - 1 \right]$  (rectangular channel)

### High speed gas flow

Nozzles: Mass flow given by  $\dot{m} = AC_d \sqrt{\frac{2n}{(n-1)}} P_0 P_0 \left[ \left( \frac{P_0}{P_0} \right)^{2/n} - \left( \frac{P_0}{P_0} \right)^{n+1} \right]$

Critical pressure ratio  $\frac{P_0^*}{P_0} = \left( \frac{2}{n+1} \right)^{\frac{n}{n-1}}$

Sonic velocity  $a = \sqrt{\nu p/\rho}$

where  $n = 1.3$  for steam, initially superheated  
 $= 1.135$  for steam, initially wet or dry saturated  
 $= \gamma = 1.4$  for air

For perfect gas:

Stagnation temperature  $T_0 = T \left[ 1 + \frac{(\gamma-1)}{2} M^2 \right]$

For air in isentropic flow ( $\gamma = 1.4$ )  $\frac{\dot{m} T_0}{A^* P_0} = 0.0404 \frac{kg s^{\frac{1}{2}}}{Ns}$

Turbine Ellipse Law  $\frac{\dot{m} T_0}{A^* P_0} = \left[ 1 - \left( \frac{P_0}{P_0} \right)^2 \right]^{\frac{1}{2}}$

### 8.5 Dimensionless groups

Drag coefficient  $C_d = \text{drag force}/\frac{1}{2} \rho V^2 A$   
 Discharge coefficient  $C_d = C_{\text{actual}} / \left[ C_{\text{throat}} \left( \frac{2 \rho \text{meter} / \rho}{1 - \frac{A_{\text{throat}}}{A_{\text{pipe}}} \frac{V^2}{2g}} \right)^{\frac{1}{2}} \right]$

Fourier number  $Fr = (k/\rho c_p) t / L^2$

Froude number  $Fr = V / \sqrt{gL}$

Grashof number  $Gr = g \beta T L^3 \rho^2 / \mu^3$

Mach number  $M = V / a$

Nusselt number  $Nu = hL/k$

Prandtl number  $Pr = \mu c_p / k$

Reynolds' number - general  $Re = \rho VL / \mu$

" " - rotating disc  $Re = \rho \omega D^2 / 4 \mu$

Weber number  $We = V ( \rho / \sigma )^{\frac{1}{2}}$

Pipeflow friction factor  $f = 40 D h / 2 \pi V^2$  (round pipes)

$2 g m_h / \pi V^2$  (non-circular duct)

Wall shear stress coefficient  $f = \tau_w / \frac{1}{2} \rho V^2$

### 8.6 Composition of air

	Vol. Analysis	Grav. Analysis
Nitrogen ( $N_2 = 28.013$ )	0.7809	0.7553
Oxygen ( $O_2 = 31.999$ )	0.2095	0.2314
Argon ( $A_r = 39.948$ )	0.0093	0.0128
Carbon dioxide ( $CO_2 = 44.010$ )	0.0003	0.0005

Mean Molecular Weight  $M = 28.96$

Specific Gas Constant  $R = 0.2871 \text{ kJ/(kgK)}$

### 8.7 Temperatures at the primary fixed points

Normal boiling point of oxygen (oxygen point)	-182.97°C
Triple point of water	0.01°C
Normal boiling point of water (steam point)	100.00°C
Normal boiling point of sulphur (sulphur point)	444.6°C
Normal melting point of silver (silver point)	960.8°C
Normal melting point of gold (gold point)	1063°C

### (iii) Solids

#### 8.8 Critical constants

	molecular weight	T <sub>c</sub> (K)	P <sub>c</sub> (bar)	ρ <sub>c</sub> (kg/m <sup>3</sup> )
hydrogen	2.02	33.3	13.0	31
helium (4)	4.00	5.3	2.29	69.3
water vapour	18.02	647.30	221.2	318.3
nitrogen	28.01	126.1	33.9	311
oxygen	32.00	154.4	50.4	430
carbon dioxide	44.01	304.15	73.8	468

#### 8.9 Approximate physical properties at 20°C, 1 bar (10<sup>5</sup>N/m<sup>2</sup>)

	R kJ/kgK	ρ kg/m <sup>3</sup>	c <sub>p</sub> kJ/kgK	c <sub>p</sub> /c <sub>v</sub>	μ mNs/m <sup>2</sup> secP	k W/mK
hydrogen	4.16	0.082	14.3	1.40	8.8x10 <sup>-3</sup>	1.8x10 <sup>-1</sup>
helium	2.08	0.164	5.23	1.66	1.96x10 <sup>-2</sup>	1.4x10 <sup>-1</sup>
nitrogen	0.294	1.16	1.04	1.40	1.76x10 <sup>-2</sup>	2.6x10 <sup>-2</sup>
oxygen	0.260	1.31	0.91	1.40	2.03x10 <sup>-2</sup>	2.6x10 <sup>-2</sup>
carbon dioxide	0.190	1.80	0.84	1.28	1.47x10 <sup>-2</sup>	1.7x10 <sup>-2</sup>
air	0.287	1.19	1.005	1.40	1.82x10 <sup>-2</sup>	2.6x10 <sup>-2</sup>

#### (ii) Liquids

	ρ kg/m <sup>3</sup>	c <sub>p</sub> kJ/(kgK)	μ cP	k W/(mK)	σ N/m	β 10 <sup>-3</sup> K <sup>-1</sup>
water	1,000	4.19	1.002	0.6	0.073	0.21
mercury	13,600	0.14	1.55	8.7	0.51	0.18
castor oil	960	2.20	1000	0.18	0.039	
benzene	880	1.80	0.856	0.16	0.029	
ethyl alcohol	790	2.86	1.20	0.19	0.022	1.08
engine oil	890	1.9	80	0.15	-	0.8
Freon 12	1,350	0.96	0.273	0.073	-	

	ρ kg/m <sup>3</sup>	c <sub>p</sub> kJ/(kgK)	k W/(mK)	σ μm/(mK)
duralumin	2720	0.88	170	23
steel	7850	0.46	52	11
stainless steel (18% Ni, 8% Cr)	7810	0.46	16	18
brass (65/35)	8450	0.37	120	19
concrete	2400	0.88	1.1	10-14
wood (pine)	500	2.8	0.15	0.15
firebrick	170	0.81	0.38	3-9

#### (iv) Fuels

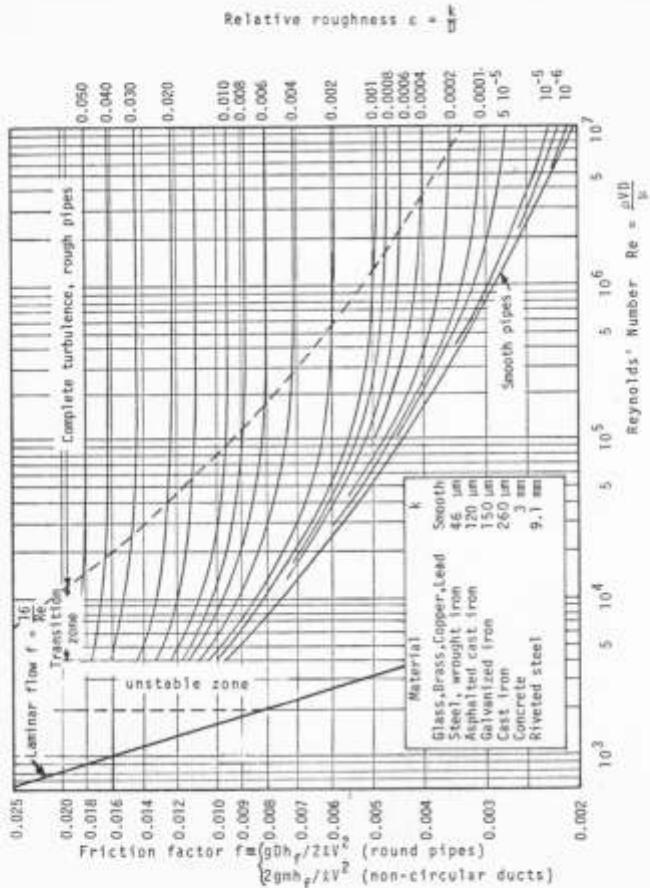
##### (a) Gases (fuels)

	Composition by Volume							Relative Density (Air) = 1	Calorific Value MJ/m <sup>3</sup> 15°C 1.01325 bar	Theoretical Air Vol/Vol	
	N <sub>2</sub>	H <sub>2</sub>	CH <sub>4</sub>	C <sub>2</sub> H <sub>6</sub>	C <sub>3</sub> H <sub>8</sub>	C <sub>4</sub> H <sub>10</sub>	C <sub>5</sub> H <sub>12</sub>				
Hydrogen	100							0.0696	12.10	10.22	2.38
Methane		100						0.5537	37.71	33.95	9.52
North Sea Gas 1.5	94.4	3.0	0.5	0.2				0.589	38.62	34.82	9.75
Propane*			1.5	91.0	2.5	5.0	1.523	93.87	86.43	23.76	
Butane*		0.1	0.5	7.2	87.0	4.2	1.941	117.75	108.69	29.92	

\* Commercial Liquid petroleum Gas (L.P.G.) See also data on liquid fuels below.

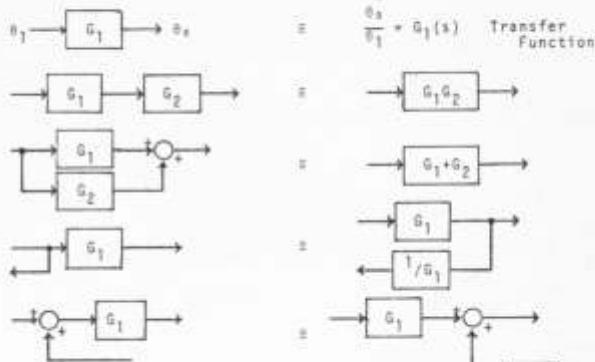
##### (b) Liquids (fuels), typical values

	Composition % Mass			Density at 15°C kg/m <sup>3</sup>	Calorific Value MJ/kg at 15°C	
	C	H	S		Gross	Net
Propane*	82.0	18.0		505	50.0	46.3
Butane*	81.9	17.0		575	49.3	45.8
Petrol	85.5	14.4	0.1	733	46.9	43.7
Kerosene	85.9	14.0	0.1	780	46.5	43.4
Diesel (Gas Oil)	85.7	13.4	0.9	840	45.4	42.4

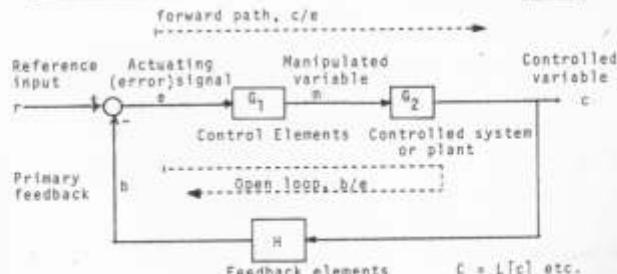


## 9. AUTOMATIC CONTROL

## 1. Block Diagrams



## 2. Feedback Notation



$$\text{Input/Output closed loop transfer function} = \frac{C}{R} = \frac{G_1 G_2}{1 + G_1 G_2 H}$$

$$\text{Input/Error closed loop transfer function} = \frac{C}{R - r} = \frac{1}{1 + G_1 G_2 H}$$

$$\text{Characteristic equation} = 1 + G_1 G_2 H = 0$$

$$G_1 G_2 H \triangleq KGH = \frac{K}{s} \prod_{i=1}^m (s + z_i) \quad -z_1, \dots, -z_n \quad \text{zeros and poles}$$

$$= \frac{K}{s} \prod_{i=1}^n (s + p_i) \quad 1 \quad \text{system type number}$$

$$n \quad \text{system order number}$$

### 3. Stability Criteria for Linear Systems

3.1 Root location: No closed loop system pole may have positive real part

### 3.2 Routh Array

Characteristic equation  $a_n s^n + a_{n-1} s^{n-1} + \dots + a_1 s + a_0 = 0$

	1	2	3	"
$n$	$a_n$	$a_{n-2}$	$a_{n-4}$	"
$n-1$	$a_{n-1}$	$a_{n-3}$	$a_{n-5}$	"
$n-2$	$b_1$	$b_2$	$b_3$	"
$n-3$	$c_1$	$c_2$	$c_3$	"
"	"	"	"	"
$b_1 = \frac{a_{n-1}a_{n-2} - a_n a_{n-3}}{a_{n-1}}$	$b_2 = \frac{a_{n-1}a_{n-4} - a_n a_{n-5}}{a_{n-1}}$			
$c_1 = \frac{b_1 a_{n-3} - a_{n-1} b_2}{b_1}$	$c_2 = \frac{b_1 a_{n-5} - a_{n-1} b_3}{b_1}$	etc.		

Number of closed loop poles with positive real part = number of sign changes in column 1.

### 3.3 Nyquist Encirclement

$$P = N + Z$$

$N$  = number of clockwise encirclements of  $(-1, j0)$  by open loop locus

$P$  = number of closed loop poles with positive real part

$Z$  = number of open loop poles with positive real part

3.4 Gain Margin =  $|KG(j\omega_g)H(j\omega_g)|^{-1}$ ,  $\omega_g$  such that

$$\angle KG(j\omega_g)H(j\omega_g) = -180^\circ$$

3.5 Phase Margin =  $180^\circ + \angle KG(j\omega_p)H(j\omega_p)$ ,  $\omega_p$  such that

$$|KG(j\omega_p)H(j\omega_p)| = 1$$

### 4. Rules of Root Locus Sketching

4.1 Every point,  $a$ , on the root locus for positive  $K$  satisfies

$$|G(a)H(a)| = 1/K$$

$$\angle G(a)H(a) = (1+2k)180^\circ \quad k = 0, \pm 1, \pm 2, \dots$$

4.2 The number of branches of the root locus is equal to the number of poles.

4.3 Branches of the locus can be considered to start on the poles ( $K = 0$ ) and terminate on zeros ( $K = \infty$ ).

4.4 Points of the root locus exist on the real axis to the left of an odd number of poles plus zeros.

4.5 The locus is symmetrical with respect to the real axis.

4.6 The angles of asymptotes,  $\alpha_k$ , to the root locus are given by

$$\alpha_k = \frac{\pm(2k+1)\pi}{n-n}$$

$k = 0, 1, 2, \dots$

4.7 The intersection of the asymptotes and the real axis occurs at  $s_r$

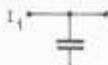
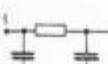
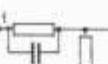
$$s_r = -\frac{\sum p_i - \sum z_i}{n-n}$$

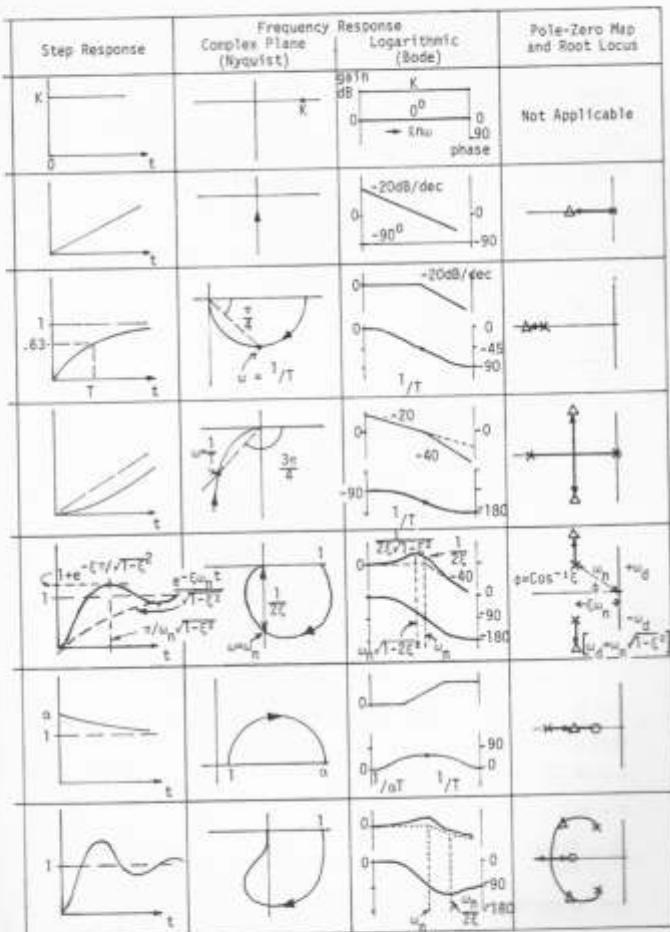
4.8 The locus leaves the real axis or arrives at it at points  $a$  where  $a$  is given by

$$\frac{d}{da} [\text{Im}(KG(a)H(a))] = 0$$

4.9 The intersection of the root locus and the imaginary axis can be found by application of Routh's Stability criteria.

## 5. TABLE OF CHARACTERISTIC SYSTEMS

Typical Example			Basic form of transfer function $G(s)$
Electrical	Dynamic	Hydraulic	
			$K$
			$\frac{1}{s}$
			$\frac{1}{s(T+s)}$
			$\frac{1}{s(1+Ts)}$
			$\frac{\omega_n^2}{s^2 + 2\xi_n s + \omega_n^2}$
			$\frac{1+\xi Ts}{1+Ts}$
			$\frac{\omega_n^2(1+2\xi s + \omega_n^2)}{s^2 + 2\xi s \omega_n^2 + \omega_n^2}$



## 10. ELECTRICITY

### Ohm's Law

$$V = IR, \quad R = \frac{V}{I}, \quad I = \frac{V}{R}$$

### Power

$$\text{DC Power} = VI = I^2R = V^2/R$$

$$\text{AC Power} = Re(VI) = |V||I|\cos\phi$$

### Resistance

$$1 = \frac{1}{\rho_0(1+\alpha T)} \frac{dV}{dx} \quad R = \left| \frac{\rho_0(1+\alpha T)}{a} \right| dx$$

### Inductance

$$e = -L \frac{di}{dt} \quad i = -\frac{1}{L} \int \frac{V}{t} dt$$

$$L = N^2 \mu_0 A B^2 / E$$

$$\text{for L-R circuit decay } i = I e^{-Rt/L}$$

$$\text{Stored energy} = \frac{1}{2} L I^2$$

### Capacitance

$$Q = CV = \int i dt$$

$$i = \frac{dQ}{dt} = C \frac{dV}{dt}$$

$$C = \epsilon_0 \epsilon_r (n-1) a/d, \text{ for } n \text{ parallel plates}$$

$$\epsilon_0 = 8.85 \cdot 10^{-12} \text{ F m}^{-1}$$

$$\text{for RC circuit discharge } i = -I e^{-t/RC}$$

$$\text{Stored energy} = \frac{1}{2} C V^2$$

$$F = \frac{1}{2} \epsilon_0 \epsilon_r \delta \left( \frac{V}{d} \right)^2$$

### Electrostatics

$$F = \frac{q_1 q_2}{4\pi\epsilon_0 r^2} \quad E = \epsilon_0 E = \text{--ve grad} V$$

$$Q = \int D \cdot dS (\text{--ve}) \quad D = \epsilon_0 \epsilon_r E$$

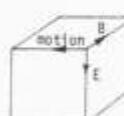
### Electromagnetism

$$E = -N \frac{d\phi}{dt} \quad B = \frac{\mu_0 I}{2\pi r}$$

$$F = B I l$$

$$\frac{dH}{dt} = \frac{15 \sin \theta}{4\pi r^2}$$

$$\text{For solenoid } H = \frac{NI}{l}$$



### Magnetism

$$H = \frac{B}{\mu_0 \mu_r}$$

For a magnetic circuit

$$B = \frac{\Phi}{A}$$

$$\Phi = \frac{NI}{\frac{l_1}{\mu_1 A_1} + \frac{l_2}{\mu_2 A_2}}$$

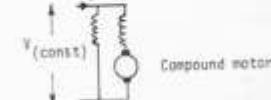
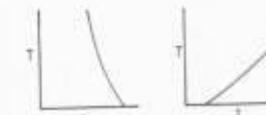
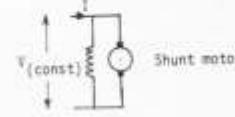
$$\text{Stored Energy Density} = \frac{1}{2} HB = \frac{1}{2} \frac{B^2}{\mu_0}$$

$$F = \left( \frac{1}{2} HB \right) a = \frac{B^2 a}{2 \mu_0}$$

### DC Machines

$$E = \frac{2\pi}{c} \frac{n}{60} p \phi \quad T = \frac{I_a Z p \phi}{2\pi c} \quad \text{where } c = 2 \text{ (wave) or } 2p \text{ (lap)}$$

$$V = E + I_a R_a$$

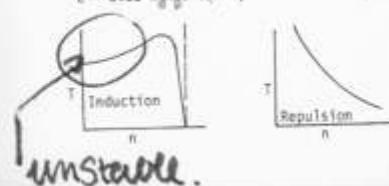


### AC Machines

$$\text{Synchronous speed} = f/p$$

$$E = 2.22 k \phi p Z f_0 (\text{rms})$$

$$T = \frac{\phi^2 s R}{R^2 + (sX_0)^2}$$



AC Circuits  $V_{rms} = \sqrt{2} V_{max}$

Series LCR

$$Z = (R^2 + (\omega L - \frac{1}{\omega C})^2)^{\frac{1}{2}}$$

$$\omega = 2\pi f$$

$$Z = R + j\omega L + \frac{1}{j\omega C}$$

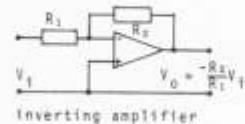
$$\text{Cos}\phi = \frac{R}{Z}$$

$$\text{At resonance } \omega = \omega_0 = \frac{1}{\sqrt{LC}} \quad Q \text{ factor} = \omega_0 L$$

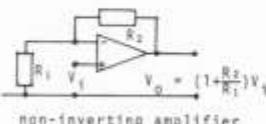


$$V_L \quad V_C \quad V_R$$

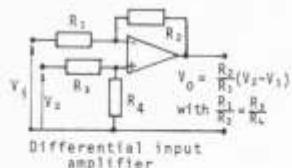
### Basic Op'Amp' Circuits



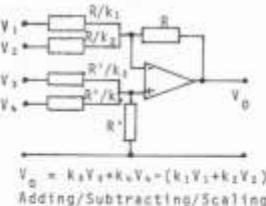
Inverting amplifier



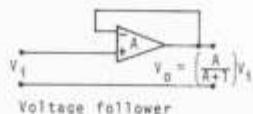
non-inverting amplifier



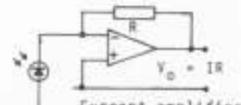
Differential input amplifier



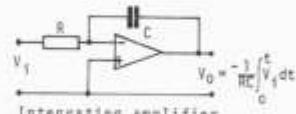
V0 = k3V3 + k4V4 - (k1V1 + k2V2)  
Adding/Subtracting/Scaling



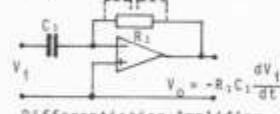
Voltage follower



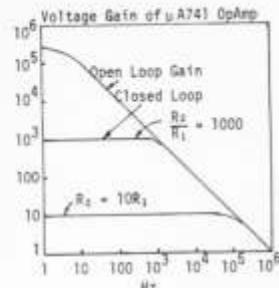
Current amplifier



Integrating amplifier



Differentiating Amplifier



### Colour Code

0	Black	2	Red	4	Yellow	6	Blue	8	Grey
1	Brown	3	Orange	5	Green	7	Violet	9	White

### Preferred Values

10, 12, 15, 18, 22, 27, 33, 39, 47, 56, 68, 82

## 11 SOIL MECHANICS

### 11.1 Soil Classification

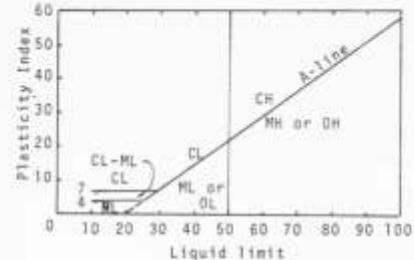
#### 1. Size Classification

CLASSIFICATION	M.I.T. Size limits mm	B.S. Sieves used for separation mm
Gravel	— 20	20 —
	6 —	6, 3 —
	2 —	2 —
Sand	— 0.6	0.6 —
	0.2 —	0.212 —
	0.06 —	0.063 —
Silt	0.02 —	—
	0.008 —	—
	0.002 —	—
Clay		

#### 2. Casagrande Soil Classification, fine grained (50% or more passing B.S. No.200 sieve)

Silts and clays (Liquid limit less than 50)	Inorganic silts, silty or clayey fine sands, with ML slight plasticity
	Inorganic clays, silty clays, sandy clays of low plasticity CL
	Organic silts and organic silty clays of low plasticity OL
Silts and clays (Liquid limit greater than 50)	Inorganic silts of high plasticity MH
	Inorganic clays of high plasticity CH
	Organic clays of high plasticity OH
Highly organic soils	Peat and other highly organic soils Pt

M silt      L low plasticity  
C clay      H high plasticity  
O organic



#### 3. Volume-weight Relationships

$$\begin{aligned}
 \text{Vol.} & \quad \text{Weight} \quad n = \frac{e}{1+e} \quad e = \frac{n}{1-n} \\
 \begin{array}{|c|c|c|c|} \hline
 1 & \text{Air} & 0 & w = \frac{Se}{S_a} \\
 \hline
 \frac{1}{2} & \text{Water} & \frac{1}{2} & S_a = \frac{S_w(1+e)}{1+e} \\
 \hline
 \frac{1}{2} & \text{Solids} & \frac{1}{2} & \gamma = \frac{G_s(1+e)}{1+e} \gamma_w \\
 \hline
 1 & G_s \gamma_w & 1 & \gamma = \frac{G_s-1}{1+e} \gamma_w = \gamma_{sat} - \gamma_w \\
 \hline
 \end{array} & \quad \gamma = \frac{G_s-1}{1+e} \gamma_w = \gamma_{sat} - \gamma_w
 \end{aligned}$$

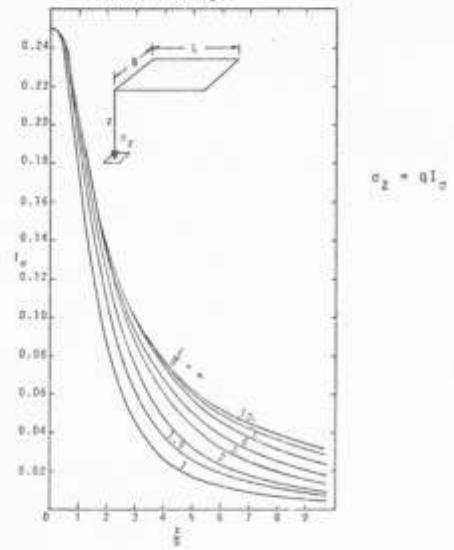
#### 4. Stratigraphic Table

##### Subdivisions of Quaternary

Era	Period	Epoch	Relative Climate	U.K. Name
Cenozoic	Quaternary	Recent	Warm (current)	Flandrian (Holocene)
		Pleistocene	Cold	Devensian
	Tertiary	Pliocene	Warm	Ipswichian
		Miocene	Cold	Woolstonian
Mesozoic	Cretaceous	Oligocene	Warm	Hoxian
		Eocene	Cold	Anglian
		Paleocene	Warm	Cromerian
	Triassic		Cold	Beestonian
Paleozoic	Permian		Warm	Pastonian
		Carboniferous	Cold	Baventian
		Devonian	Warm	Amian
		Silurian	Cold	Thurnian
	Ordovician		Warm	Ludianian
	Camrian		Cold	Waltonian
Precambrian				

## 11.2 Stresses and Displacements in Elastic Half-space

1. Vertical stress at depth  $z$  below corner of uniformly loaded rectangle



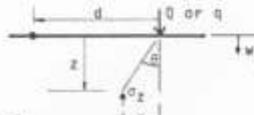
$$\sigma_z = qI_z$$

### 2. Boussinesq

(a) Point load  $q$  at surface

$$\sigma_z = \frac{3q}{2\pi z^2} \cos^2 \theta$$

$$w_s = \frac{q(1+\nu)}{24\pi E} \cosh^2 [\cos^2 \theta + 2(1-\nu)]$$



(b) Line load  $q$  at surface

$$\sigma_z = \frac{2q}{\pi z} \cos^4 \theta$$

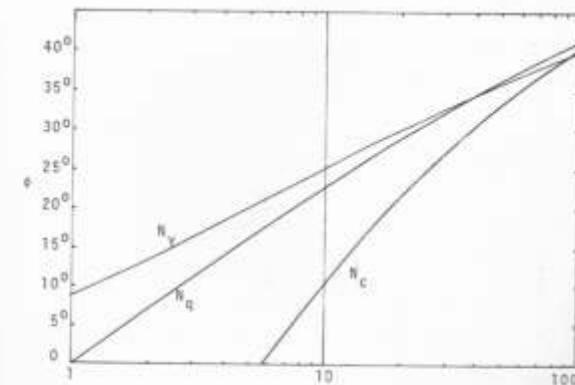
$$w_s = \frac{2q(1-\nu^2)}{\pi E} \ln \left( \frac{d}{z} \right) \text{ where displacement at } d \text{ is assumed = 0 } (d \gg x)$$

## 3. Surface displacement of uniformly loaded rectangle

L/B Ratio	I_E		
	Centre	Corner	Average
1	1.12	.56	.95
1.5	1.36	.68	1.15
2	1.53	.76	1.30
3	1.78	.89	1.53
4	1.96	.98	1.70
5	2.10	1.05	1.83
7	2.33	1.16	2.04
10	2.53	1.27	2.25
20	2.95	1.47	2.64
30	3.23	1.61	2.88
50	3.54	1.77	3.22
100	4.01	2.00	3.69
Circle	1.00	Edge .64	.85

$$w_s = qB \frac{1-\nu^2}{E} I_E$$

## 11.3 Terzaghi Bearing Capacity Factors

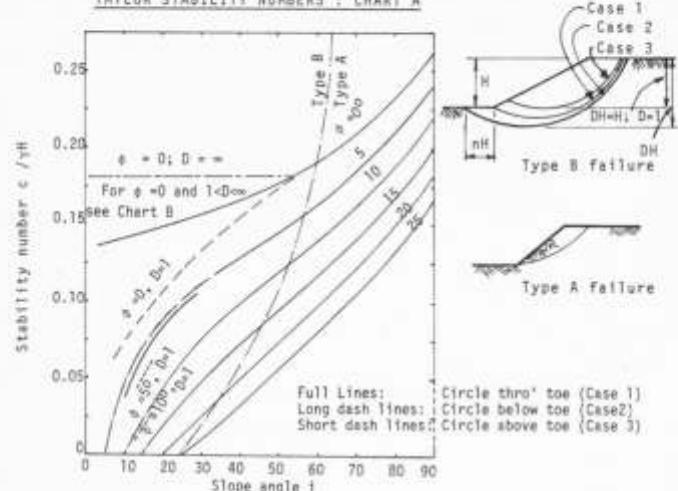


$$\left. \begin{aligned} \text{Strip footing} \quad q &= cN_c + \nu DN_q + .8y BN_y \\ \text{Square footing} \quad q &= 1.3 cN_c + \nu DN_q + .4y BN_y \\ \text{Circular footing} \quad q &= 1.3 cN_c + \nu DN_q + .3y BN_y \end{aligned} \right\} \text{FOOTING WIDTH } B$$

Note: Reduce  $c$  and  $tan\phi$  to two thirds of measured values for local shear.

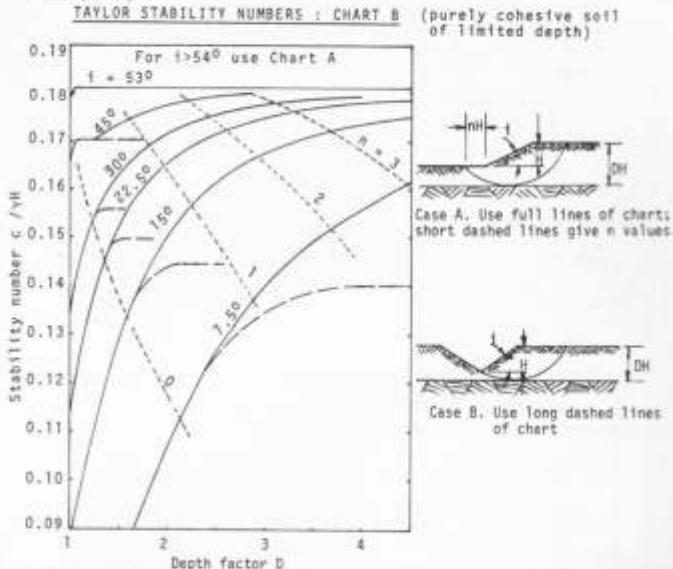
#### 11.4 Slope Stability

TAYLOR STABILITY NUMBERS : CHART A

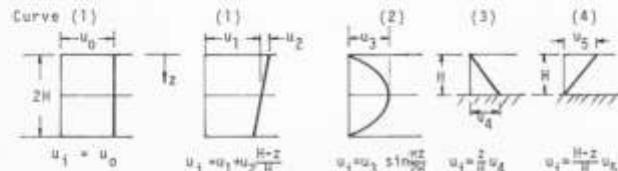


#### 11.4 (cont)

TAYLOR STABILITY NUMBERS : CHART B



#### 11.5 Consolidation-Time Curves



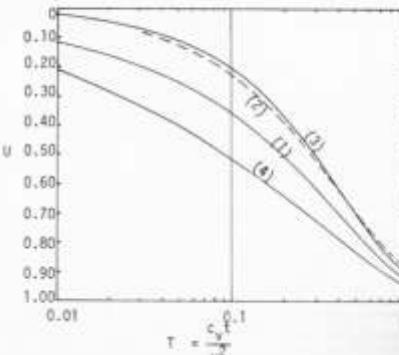
$$\text{For curve (1): } U < .60 \quad T = \frac{\pi}{4} U^2$$

$$U < .60 \quad T = -0.933 \log_{10}(1-U) \approx 0.086$$

$$T_{50} = .197$$

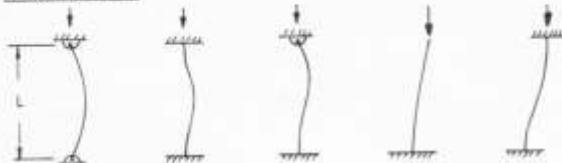
$$T_{90} = .848$$

#### 11.5 (cont)



## 12. STRUCTURES

### Buckling Loads



### Buckling Load:

$$\frac{\pi^2 EI}{L^2}, \quad \frac{4\pi^2 EI}{L^2}, \quad \frac{2.048\pi^2 EI}{L^2}, \quad \frac{\pi^2 EI}{4L^2}, \quad \frac{\pi^2 EI}{L^2}$$

### Effective Length:

$$L, \quad 0.5L, \quad 0.699L, \quad 2L, \quad L$$

### Beams bent about principal axis

$w$ is load/unit length	end slope	maximum deflection $\Delta$
	$\frac{ML}{EI}$	$\frac{ML^2}{2EI}$
	$\frac{WL^2}{2EI}$	$\frac{WL^3}{3EI}$
	$\frac{WL^3}{6EI}$	$\frac{WL^4}{8EI}$
	$\frac{ML}{2EI}$	$\frac{ML^2}{8EI}$
	$\frac{WL^2}{16EI}$	$\frac{WL^3}{48EI}$
	$\frac{WL^3}{24EI}$	$\frac{WL^4}{384EI}$
	$\frac{WL^3}{32EI}$	$\frac{WL^4}{384EI}$
$w$ is load/unit length, $b < L$	$\frac{Wac^2}{2EI}$	$\frac{Wac^3}{3EI}$
$b < L$	$b = \frac{Wac^2}{2EI}$	$a = \frac{L+b}{3}$
$b < L$	$a = \frac{L+b}{3}$	$c = \sqrt{\frac{b(L+a)}{3}}$

### Fixed End Moments

LH end conditions moment-shear	RH end conditions shear-moment	maximum deflection $\Delta$	maximum deflection position $c$
$\frac{\pi L^2}{12}$	$\frac{WL}{2}$	$\frac{\pi L^4}{304EI}$	$\frac{L}{2}$
$\frac{WL}{8}$	$\frac{W}{2}$	$\frac{WL^3}{192EI}$	$\frac{L}{2}$
$\frac{Wab^2}{L^2}$	$\frac{Wa^2(L+2a)}{L^3}$	$\frac{Wa^2b}{3EI(L+2b)^2}$	$\frac{2Lb}{L+2b}$
$\frac{6EI}{L^2}$	$\frac{12EI}{L^3}$	$\frac{12EI}{L^3}$	$\frac{6EI}{L^2}$
$\frac{Mb}{L^2}(2a-b)$	$\frac{M}{L}$	$\frac{Mb}{L^2}(2b-a)$	-
$\frac{\pi L^2}{30}$	$\frac{3aL}{20}$	$\frac{7aL}{20}$	$\frac{\pi L^4}{764EI}$
$\frac{3WL}{TE}$	$\frac{11W}{16}$	$0$	$\frac{2WL^2}{21SET}$
$\frac{Wab(L+b)}{2L^2}$	$\frac{Wa}{L} - \frac{M}{L}$	$0$	$\frac{Wa^2b}{6EI\sqrt{\frac{b}{2L+b}}}$
$\frac{\pi L^2}{8}$	$\frac{5aL}{8}$	$0$	$\frac{ba}{0.4142L}$
$\frac{5aL}{8}$	$\frac{3aL}{8}$	$0$	$\frac{\pi L^4}{192EI}$

### Relations with elastic constants

$$G = E/(2(1 + \nu)) \quad K = E/(3(1 + 2\nu))$$

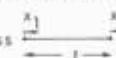
$$\text{Simple bending } \frac{M}{t} = \frac{\sigma}{y} = \frac{E}{R}$$

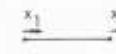
$$\text{Torsion of circular section } \frac{T}{J} = \frac{\tau}{r} = \frac{G\theta}{L}$$

### Beam stiffness Coefficients

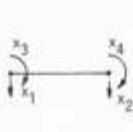
In the following the F's can be axial or shear forces, or, bending or torsional couples corresponding to the mode of deformation.

All beam and frame stiffness matrices may be built up from the following components of each beam element.

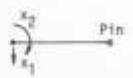
(a) axial stiffness  giving  $\begin{bmatrix} F_1 \\ F_2 \end{bmatrix} = \frac{EA}{L} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$

(b) torsional stiffness  giving  $\begin{bmatrix} F_1 \\ F_2 \end{bmatrix} = \frac{GJ}{L} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$

(c) bending stiffness and lateral deflection stiffness in one plane

 giving  $\begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \end{bmatrix} = \frac{EI}{L^3} \begin{bmatrix} 12 & -12 & 6L & 6L \\ -12 & 12 & -6L & -6L \\ 6L & -6L & 4L^2 & 2L^2 \\ 6L & -6L & 2L^2 & 4L^2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}$

In each case if one end is fixed and considered as a reaction, its deflections and forces may be ignored with a corresponding reduction of the stiffness matrix. Another possible form of reaction for case (c) occurs if the reaction end is pinned. Then the stiffness matrix components for the other end are given by

(c)(i)  giving  $\begin{bmatrix} F_1 \\ F_2 \end{bmatrix} = \frac{EI}{L^2} \begin{bmatrix} 3 & 3L \\ 3L & 3L^2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$   
or

(c)(ii)  giving  $\begin{bmatrix} F_1 \\ F_2 \end{bmatrix} = \frac{EI}{L^2} \begin{bmatrix} 3 & -3L \\ -3L & 3L^2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$

A general plane frame element will have components (a) and (c) and require a  $6 \times 6$  stiffness matrix. A general space frame element will require components of (a), (b) and (c) - the latter twice for two planes of bending - and will require a  $12 \times 12$  stiffness matrix. The three modes of deflection (a), (b), (c) are orthogonal and may be combined into larger matrices with 0's in all unspecified positions. Space frame elements will, in general, have different values of I in the two principal planes of bending.

### Shear

Shear flow per unit length of wall resulting from the applied shear forces  $S_x, S_y$  is



$$q = tr_{xs} = \frac{(-S_x)}{I_{yy}I_{zx} - (I_{yz})^2} \left( I_{yy} \int_A z dA - I_{yz} \int_A y dA \right)$$

$$+ \frac{(-S_y)}{I_{yy}I_{zx} - (I_{yz})^2} \left( I_{zz} \int_A y dA - I_{yz} \int_A z dA \right)$$

The resultant force from this shear flow acts through the SHEAR CENTRE.

### Torsion

$$\text{For a circular section } \frac{T_x}{J} = \frac{\tau}{r} = \frac{G\theta}{L}$$

$$J = \frac{\pi D^4}{32} \text{ for a solid section}$$

$$= \frac{\pi}{32} (D_{\text{outer}}^4 - D_{\text{inner}}^4) \text{ for a hollow section}$$

For a thin walled closed section

$$T_x = 2Aq$$

$$= \frac{4A^2G}{\pi ds} \cdot \frac{d}{L}$$



For a thin rectangular section

$$T_x = \frac{dt^2}{J} \tau_{zx, \text{max}}$$

$$= \frac{dt^3G}{J} \frac{d}{L}$$



### Asymmetric Bending

in terms of general axes

$$\sigma_{xx} = \frac{p_x}{A} + \frac{M_y(zI_{zx} - yI_{yz})}{I_{yy}I_{zx} - (I_{yz})^2}$$

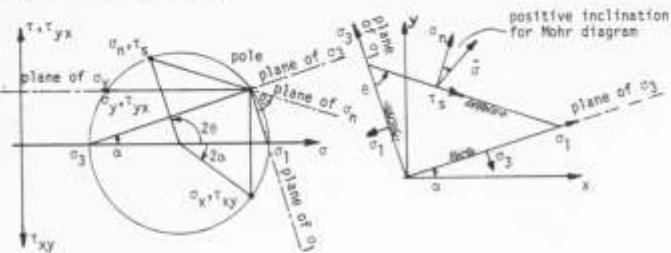
$$- \frac{M_z(yI_{yy} - zI_{yz})}{I_{yy}I_{zx} - (I_{yz})^2}$$

When the principal axes m,n lie in directions y,z, then:

$$\sigma_{xx} = \frac{p}{A} + \frac{mM_m}{I_{mm}} - \frac{mM_n}{I_{nn}}$$

### Stress and strain transformations

#### Mohr circle of stresses



Equilibrium of prism in  $\sigma_1, \sigma_3$  directions gives

$$\sigma_1 \cos \theta = \sigma_3 \cos \theta + \tau_s \sin \theta$$

$$\sigma_3 \sin \theta = \sigma_1 \sin \theta - \tau_s \cos \theta$$

$$\text{Then: } \sigma_1 \cos^2 \theta + \sigma_3 \sin^2 \theta = \sigma_1 + \frac{\sigma_1}{2}(1 + \cos 2\theta) + \frac{\sigma_3}{2}(1 - \cos 2\theta)$$

$$= \frac{\sigma_1 + \sigma_3}{2} + \frac{\sigma_1 - \sigma_3}{2} \cos 2\theta$$

$$(\sigma_1 - \sigma_3) \sin \theta \cos \theta = \tau_s + \frac{\sigma_1 - \sigma_3}{2} \sin 2\theta$$

$$\text{Also: } \sigma_1 = \frac{\sigma_x + \sigma_y}{2} + \tau_{\max}; \sigma_3 = \frac{\sigma_x + \sigma_y}{2} - \tau_{\max}; \tau_{\max} = \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + (\tau_{xy})^2}$$

$$\text{and: } \tan 2\theta = \frac{-2\tau_{xy}}{\sigma_x - \sigma_y}$$

#### Two-dimensional strain system

$\epsilon_x, \epsilon_y, \gamma$  are direct strains 'corresponding' to  $\sigma_x, \sigma_y, \tau_{xy}$

$\frac{\gamma_{xy}}{2}, \frac{\gamma}{2}$  are shear strains 'corresponding' to  $\tau_{xy}, \tau$

#### Three-dimensional stress system

If the principal stresses are  $\sigma_1, \sigma_2, \sigma_3$ , the principal shear stresses are  $(\sigma_1 - \sigma_2)/2, (\sigma_2 - \sigma_3)/2$  and  $(\sigma_3 - \sigma_1)/2$ .

Strain energy per unit volume  $U$  may be expressed as

$$U = (\sigma_1 + \sigma_2 + \sigma_3)^2 / 16K$$

$$+ [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] / 12G$$

### 13. SYMBOLS INDEX

#### GREEK ALPHABET

$\alpha, \alpha$	alpha	$\eta, \eta$	eta
$\beta, \beta$	beta	$\theta, \theta$	theta
$\gamma, \gamma$	gamma	$\iota, \iota$	iota
$\delta, \delta$	delta	$\kappa, \kappa$	kappa
$\epsilon, \epsilon$	epsilon	$\pi, \pi$	pi
$\zeta, \zeta$	zeta	$\lambda, \lambda$	lambda
		$\mu, \mu$	mu
		$\rho, \rho$	rho
		$\sigma, \sigma$	sigma
		$\omega, \omega$	omega
		$\tau, \tau$	tau
		$\upsilon, \upsilon$	upsilon
		$\phi, \phi$	phi
		$\chi, \chi$	chi
		$\psi, \psi$	psi

#### MATHEMATICAL SYMBOLS

$L\{ \cdot \}$	Laplace Transform
$\triangle$	defined as
$\sum$	repeated summation
$\prod$	repeated multiplication
$\partial$	partial differential
$ z $	modulus
$\nabla$	Laplace differential, Del, Nabla
$\mathbf{v}$	vector
$\hat{\mathbf{v}}$	unit vector
$\perp$	at right angles to
$\cdot$	scalar (dot) product
$\times$	vector (cross) product
$\text{Re } \cdot$	real part of complex number
$\text{Im } \cdot$	imaginary part of complex number

Symbol	Page No. of use		Recommended S.I. Unit
$a$	51	velocity of sound	m/s
$a$	38	lattice parameter	m
$a$	41	$\frac{1}{2}$ crack length	m
$a$	60	area	$\text{m}^2$
$a$	37	acceleration	$\text{m/s}^2$
$A$	48, 50	area	$\text{m}^2$
$A$	38	Atomic weight	-
$A$	47	availability function (non-flow)	kJ
$B$	47	availability function (flow)	kJ
$B$	60	magnetic flux density	T
$B$	66, 67	breadth of footing	m

* of specified fluid			
c	67	cohesion	$\text{kN/m}^2$
c	49	velocity	$\text{m/s}$
$c_p, c_v$	47	specific heat	$\text{kJ/kgK}$
c	69	coefficient of consolidation	$\text{m}^2/\text{s}$
c	60	capacitance	F
c	39	concentration	$\text{mol/m}^3$
c	50	Chézy coefficient	$(\text{m}^2/\text{s})$
C <sub>d</sub>	50, 51	discharge coefficient	-
C <sub>d</sub>	51	drag coefficient	-
C <sub>d</sub>	38	interatomic spacing	m
d <sub>1</sub>	38	Interplanar spacing	m
d	50	depth of flow	m
d <sub>1</sub> , d <sub>2</sub>	50	" " before jump, after jump	m
D	51, 54	diameter	m
D	39	diffusion coefficient	$\text{m}^2/\text{s}$
D	67	depth of overburden	m
D	68, 69	depth factor	-
E	65	void ratio	-
E	41, 70	Young's Modulus	$\text{N/m}^2$
$\Delta E$	38	energy difference	J
f	51	supply frequency	Hz
f	54	friction factor	-
f	51	wall shear stress coefficient	-
f	47	specific Helmholtz free energy function	$\text{kJ/kg}$
F	47	Helmholtz free energy function	J
F, F <sub>1</sub>	50, 51	Froude Number, before jump	-
F	60	force	N
g	47	specific Gibbs free energy function	$\text{kJ/kg}$
G <sub>s</sub>	65	specific gravity of solids	-
G <sub>s</sub>	41	Gibbs free energy function	$\text{kJ}^\circ\text{K}$
G	41, 72	modulus of rigidity	$\text{N/m}^2$
G <sub>1</sub> , G <sub>2</sub> , G	55	transfer function	-
h <sub>f</sub>	61, 54	frictional head loss	$\text{m}^2$
h <sub>f</sub>	47	specific enthalpy	$\text{kJ/kg}$
h	51	heat transfer coefficient	$\text{W}^\circ(\text{m}^\circ\text{K})$
H	47	enthalpy	J
H	60	magnetising force magnetic field strength	A/m
H	55	transfer function	-
i	60	current	A
i	35, 70	second moment of area	$\text{m}^4$
I	35	moment of inertia	$\text{kgm}^2$
J	39	diffusion flux	$\text{kg}/(\text{m}^2\text{s})$
k	48, 51	thermal conductivity	$\text{W}/(\text{mK})$
k	54	surface roughness	$\mu\text{m}$
k	35, 49	radius of gyration	m
k <sub>d</sub> , k <sub>p</sub>	61	distribution factor, pitch factor of winding	-
k <sub>d</sub>	55	gain constant	-
K	41	stress intensity factor	$\text{Mm}^{-1/2}$
K	41, 72	bulk modulus	$\text{N}/\text{m}^2$
K <sub>I</sub>	41	stress intensity range	$\text{Mm}^{-1/2}$
K <sub>p</sub>	47	equilibrium constant	$(\text{atmos})^{1/n}$
L	51	length	m
L	60	length of conductor	m
L	51	characteristic length	m
L	60	inductance	H
m	47	mass	kg
m	51, 54	mean hydraulic radius	m
m	47, 50	mass flowrate	$\text{kg/s}$

M	70	moment	-
M	51	Mach number	-
n	65	porosity	-
n	61	speed of rotation	r/min
n	50	Manning roughness coefficient	-
n	38	atoms per unit cell	-
n <sub>i</sub>	41	total cycles at stress amplitude	-
n <sub>p</sub>	41	total cycles to failure at strain amplitude	-
n <sub>s</sub>	41	" " " " stress	-
N	60, 61	number of turns	-
N	7, 38	Avogadro's number	$\text{kg}/(\text{kgmol})$
N	47	cycles per unit time	Hz
N <sub>F</sub>	39	total number of atoms	-
P	30	probability	-
P	47	mean effective pressure	$\text{N}/\text{m}^2$
P <sub>B</sub>	61	number of pole pairs	-
P	47	thermodynamic probability or No. of quantum states	-
P <sub>A</sub>	47	engine indicated power	$\text{N}/\text{m}^2$
P	66, 67	surface normal stress	$\text{N}/\text{m}^2$
P	48	heat flowrate per unit area emissive power	$\text{W}/\text{m}^2$
Q <sub>B</sub>	48	emissive power for black body	-
Q	39	activation energy	J
Q	47	heat (input + ve)	$\text{J}/\text{s}$
Q	49	volumetric flowrate	$\text{m}^3/\text{s}$
Q	41	crack shape factor	-
Q	60	charge	C
R	41	r.m.s. of stress	$\text{MN}/\text{m}^2$
R	60, 61	resistance, resistance per phase	$\Omega$
R	50	hydraulic radius	m
R	47	characteristic gas constant	$\text{kJ}/(\text{kgK})$
R	47	Universal gas constant	$\text{kJ}/(\text{kgmolK})$
S <sub>D</sub>	47	specific entropy	$\text{kJ}/(\text{kgK})$
S	61	fractional slip	-
S	65	degree of saturation	-
S <sub>u</sub>	47	entropy	$\text{kJ}/\text{K}$
S	50	channel slope in uniform flow	-
S <sub>F</sub>	50	friction slope	-
S <sub>F</sub>	50	invert slope	-
t <sup>0</sup>	37	time	s
T	68	time factor	-
T	61	torque	Nm
T	50	water surface width	m
T	47	temperature (absolute)	K
$\Delta T$	48	temperature difference	°C
T	43	glass transition temperature	K
u <sub>g</sub>	47	specific internal energy	$\text{kJ}/\text{kg}$
u	37	velocity	$\text{m}/\text{s}$
u	68	pore pressure	$\text{N}/\text{m}^2$
U	68	degree of consolidation	-
U	47	internal energy	$\text{J}/\text{kg}$
V	67	specific volume	$\text{m}^3/\text{kg}$
V	37	velocity	$\text{m}/\text{s}$
V <sub>0</sub>	47	molar volume	$\text{m}^3/\text{kgmol}$
V	60	voltage	V
V	38, 49	volume	$\text{m}^3$
V	38	volume of unit cell	$\text{m}^3$
V	50, 51	velocity	$\text{m}/\text{s}$
V <sub>s</sub>	47	cylinder swept volume	$\text{m}^3$

w	65	water content	-
w <sub>s</sub>	65, 67	surface displacement	m
w <sub>s</sub>	47	work (output, +ve)	kJ
w <sub>o</sub>	61	leakage reactance per phase	0
w <sub>d</sub>	49	change in specific energy through a machine	J/kg
z	49	potential head	m*
z	61	number of armature conductors	-
z	62	impedance	Ω
a	41	coefficient of linear expansion	μm/(mK)
a	60	resistance coefficient	Ω/K
β	51	coefficient of volumetric expansion	K <sup>-1</sup>
γ	65	unit weight of soil	kN/m <sup>3</sup>
γ	47, 50	specific heat ratio	-
γ <sub>w</sub>	65	unit weight of water	kN/m <sup>3</sup>
γ <sub>sat</sub>	65	unit weight of saturated soil	kN/m <sup>3</sup>
γ <sub>s</sub>	65	submerged unit weight of soil	-
c	54	relative roughness	-
c <sub>0,ε<sub>r</sub></sub>	60	permittivity, free space, relative	F/m, -
c <sub>ε</sub>	48	emissivity	-
c <sub>p</sub>	41	plastic straining range	μm/m <sup>2</sup>
η <sub>p</sub>	49	viscosity (dynamic)	mNs/m <sup>2</sup>
η <sub>0,η<sub>f</sub></sub>	60	permeability of free space, relative	m <sup>2</sup> /s, -
μ	37	dynamic viscosity	mNs/m <sup>2</sup>
v	72, 41, 66, 67	Poisson's ratio	-
ε	58, 23	damping ratio	-
ρ <sub>0</sub>	60	resistivity	Ωm
ρ <sub>0</sub>	41, 42, 43, 51	density	kg/(m <sup>3</sup> )
σ	48	Stefan-Boltzmann constant	W/(m <sup>2</sup> K <sup>4</sup> )
σ	51	surface tension in contact with air	N/m
σ <sub>y</sub>	41	proof or yield stress	N/m <sup>2</sup>
σ <sub>f</sub>	41	ultimate (failure) stress	N/m <sup>2</sup>
σ <sub>f</sub>	49, 51	shear stress	N/m <sup>2</sup>
φ	67	friction angle of soil	0
φ	60, 61	magnetic flux, flux per pole	Wb
w	70, 71	load per unit length	N/m
w	51	angular velocity	rad/s
w <sub>n</sub>	58	natural frequency	rad/s
w <sub>0</sub>	23, 62	natural frequency	rad/s
w <sub>d</sub>	59	damped natural frequency	rad/s

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